^{3}He Based Gaseous Neutron Detectors

Bo Yu

Brookhaven National Laboratory

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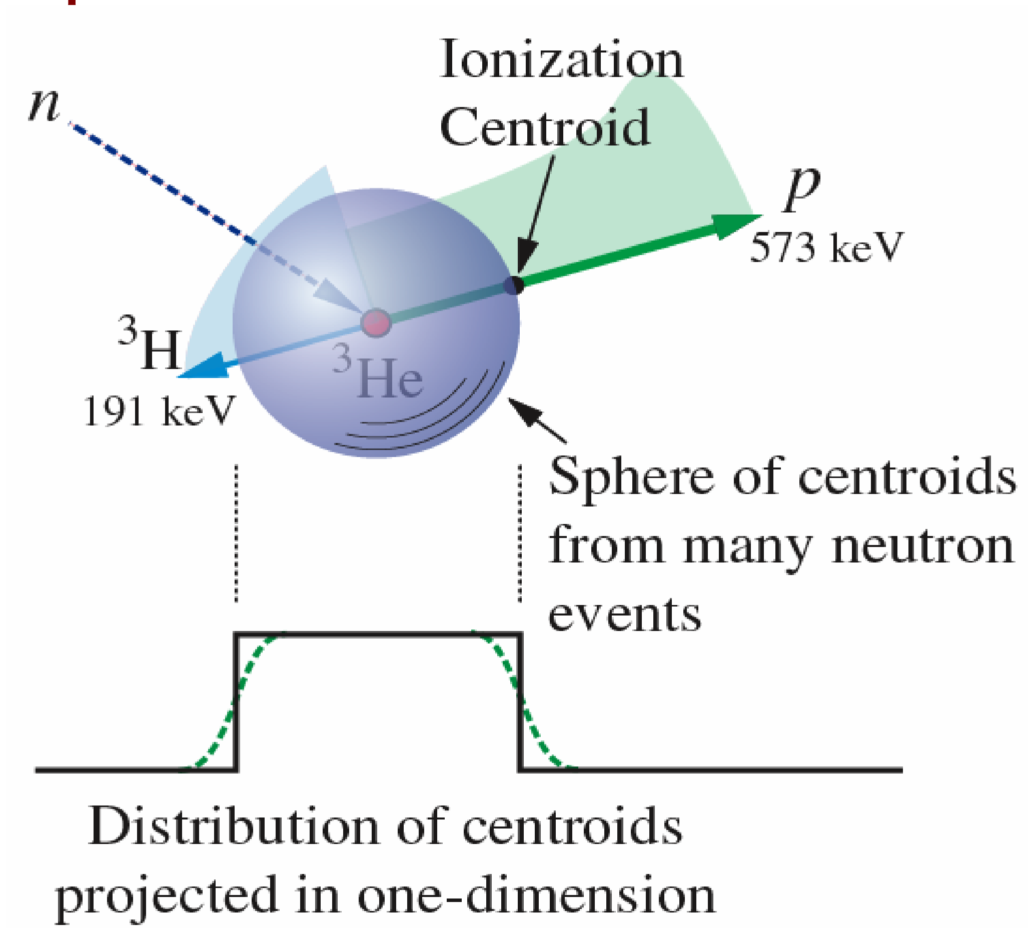
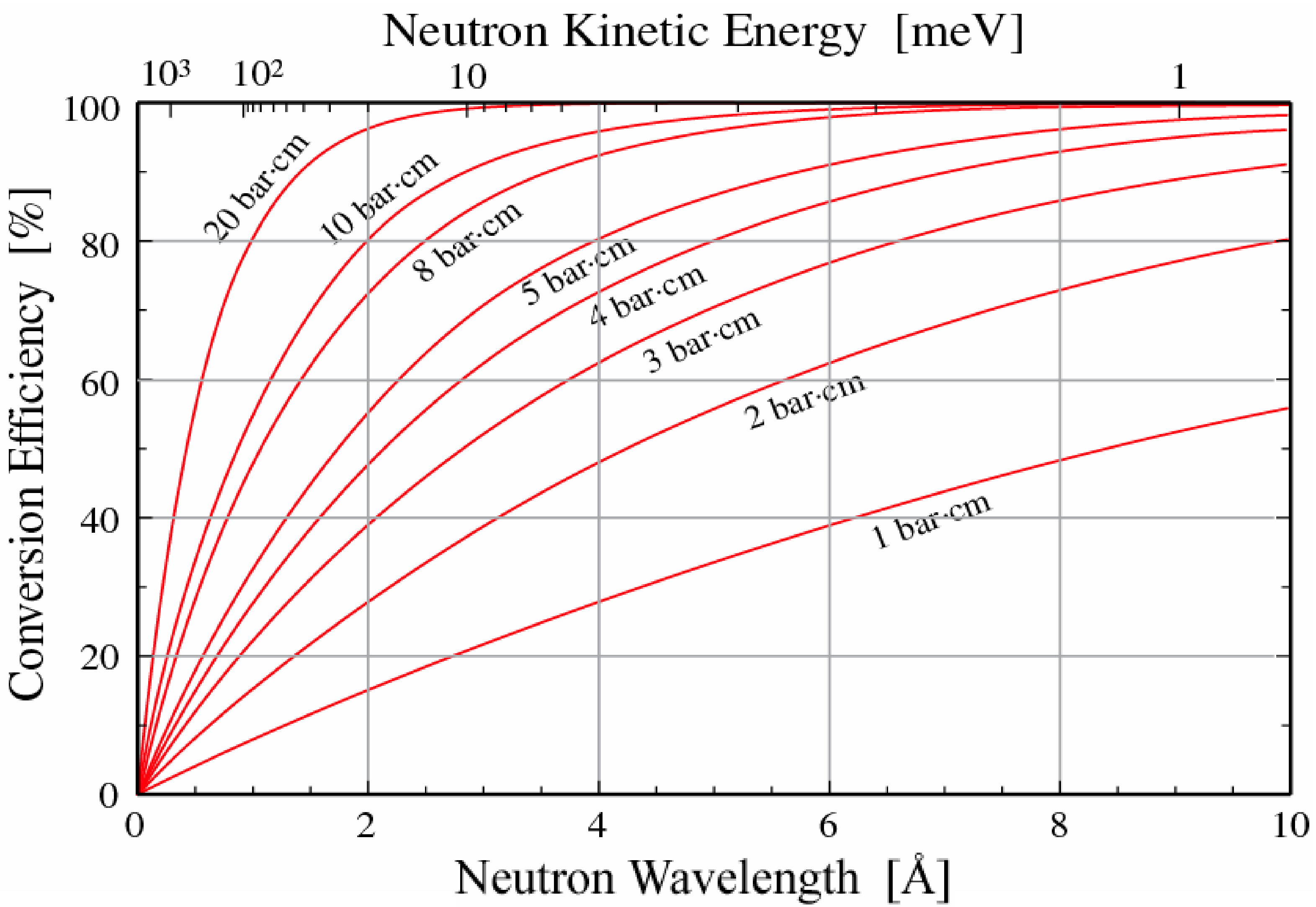
Thermal Neutron Detection in ^{3}He and Position Resolution Limit

$n + {}^3He \rightarrow p + {}^3H + 764\ keV$ $\longrightarrow$ ~25000 electron-ion pairs

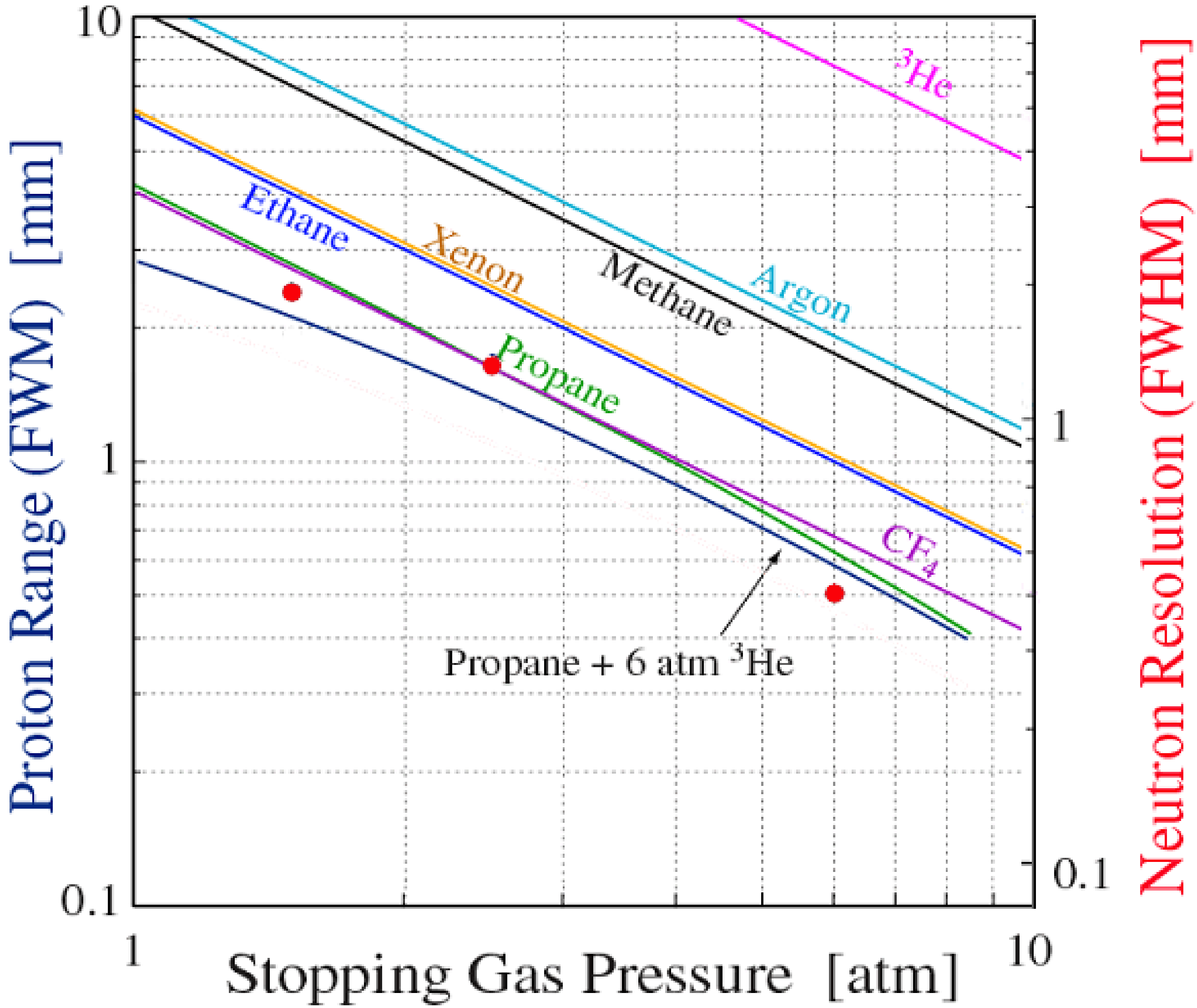


FWHM ~ 0.8 x proton range
(~ 4mm in 1 atm. Propane / CF_4)

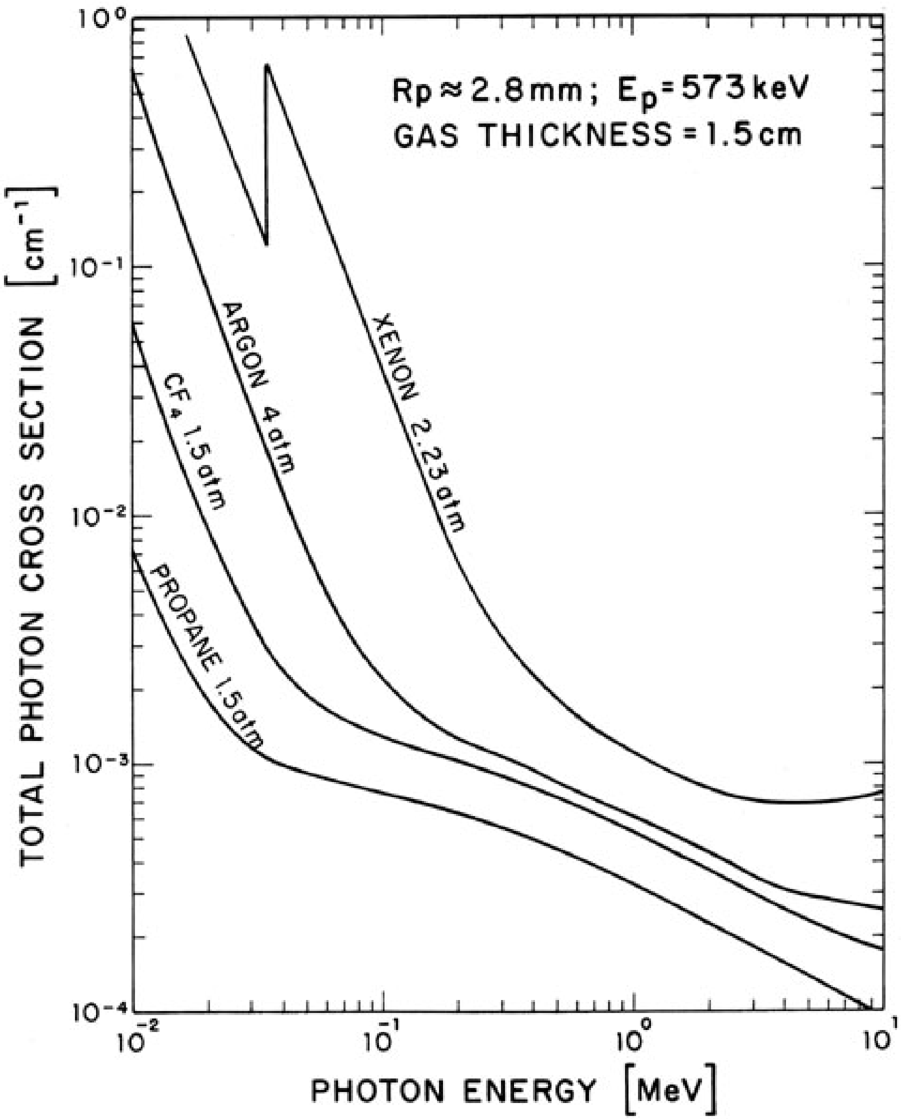
Conversion Efficiency of ^{3}He Filled Detectors



Proton Range in Common Stopping Gases



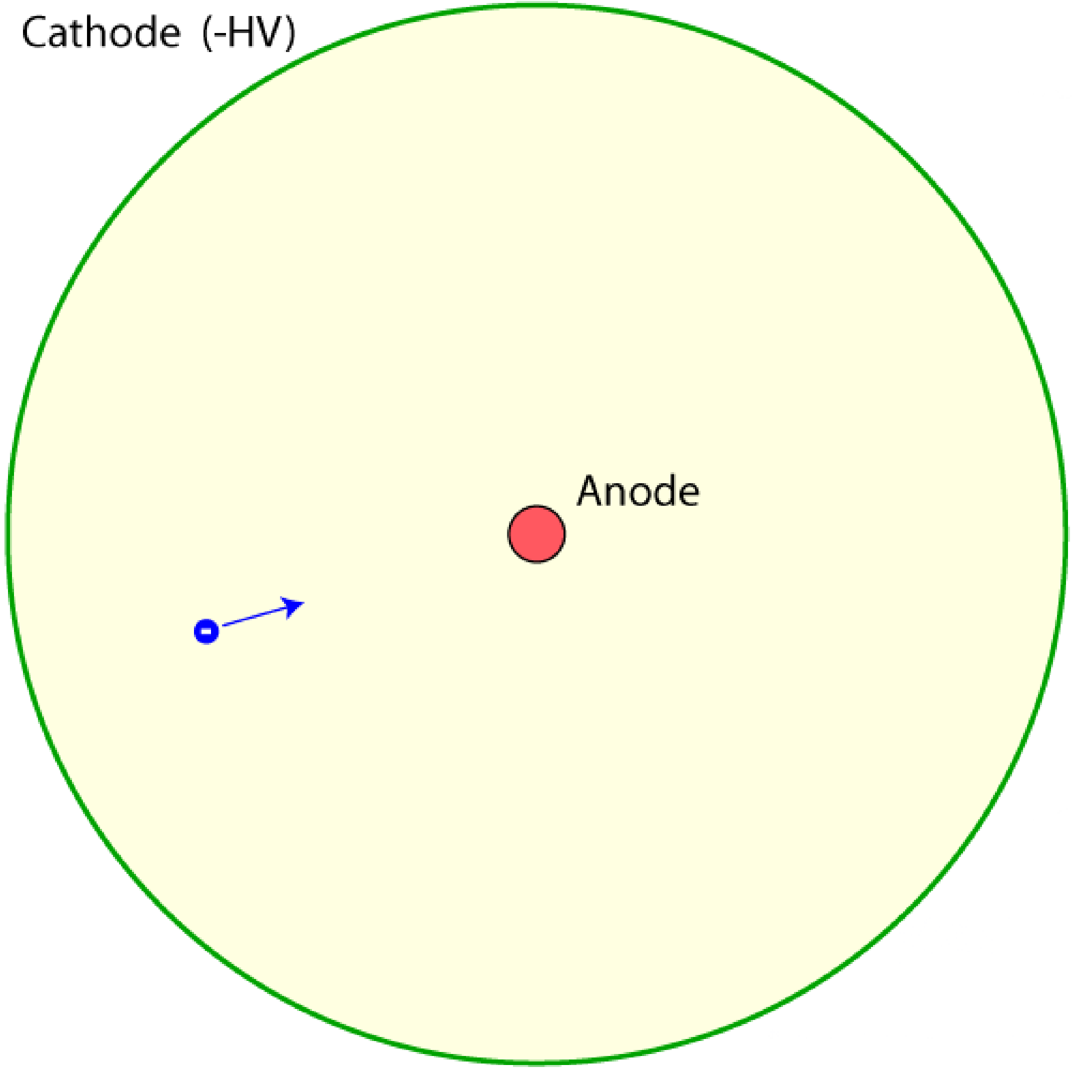
Gamma Sensitivity of Stopping Gases



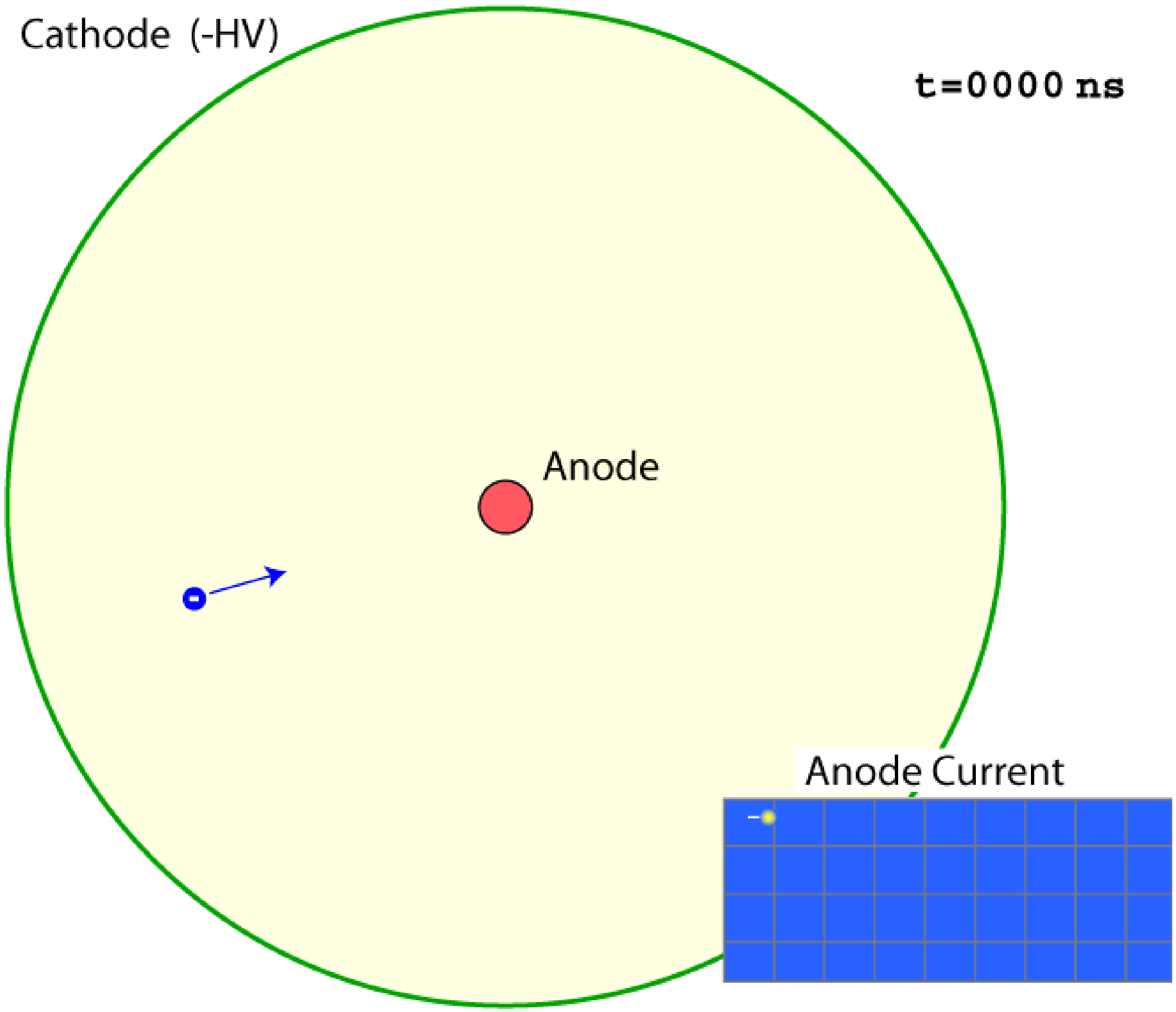
In general, the ionization density from gamma induced electrons (photo and Compton) are much lower than that of the proton / triton tracks.

However, larger energy deposition long electron tracks are possible in certain directions in the chamber. The gamma rejection or neutron sensitivity will be degraded in a system where signal summed over a large area is used for trigger or position encoding, and / or a system with low trigger threshold due to large gain variation and wall effect.

Operating Principle of a Proportional Counter

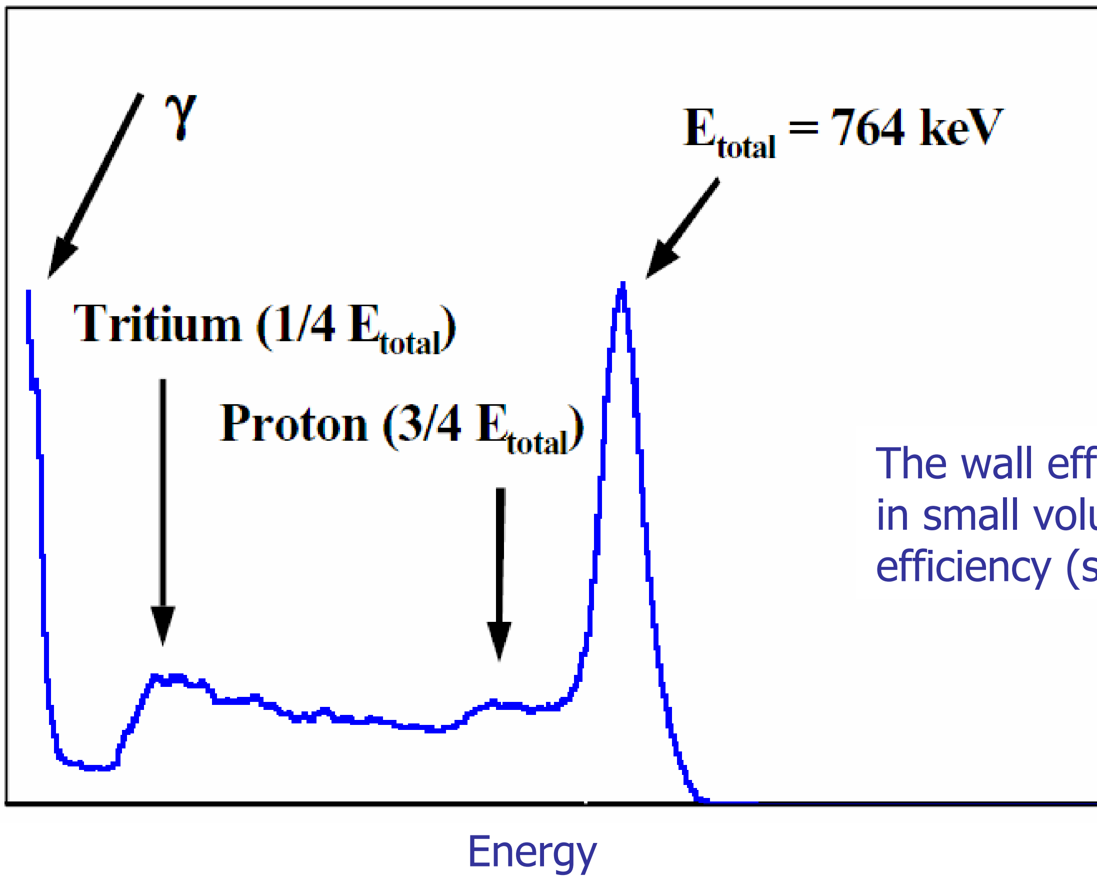


Operating Principle of a Proportional Counter



^{3}He Pulse Height Spectrum (Wall Effect)

In a properly designed and constructed detector, the neutron peak is well resolved and the pulse heights from gamma events are very low. This pulse height spectrum demonstrates the excellent energy resolution of a MSGC and low gamma sensitivity.



The wall effect is more pronounced in small volume and/or too high efficiency (slow neutrons).

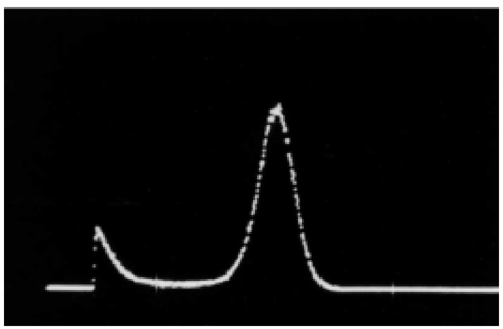
B. Guerard, presented at the Workshop on PSND Berlin, 2001

Operating in Low Gas Gain

Energy resolution degrades as the gas gain increases in a MWPC.

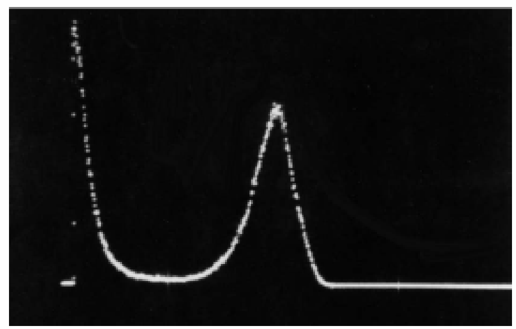
Consequences: gamma rejection, detection efficiency, stability and longevity.

$V_a - V_c = 4.2$ kV



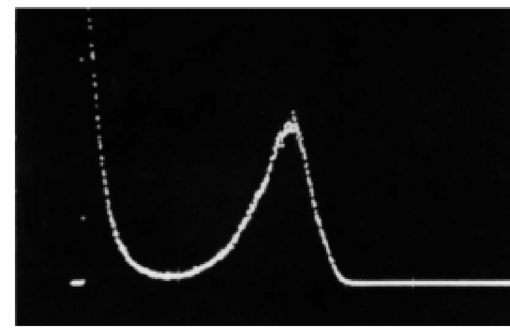
Gas Gain ~ 13

$V_a - V_c = 4.66$ kV



Gas Gain ~ 40

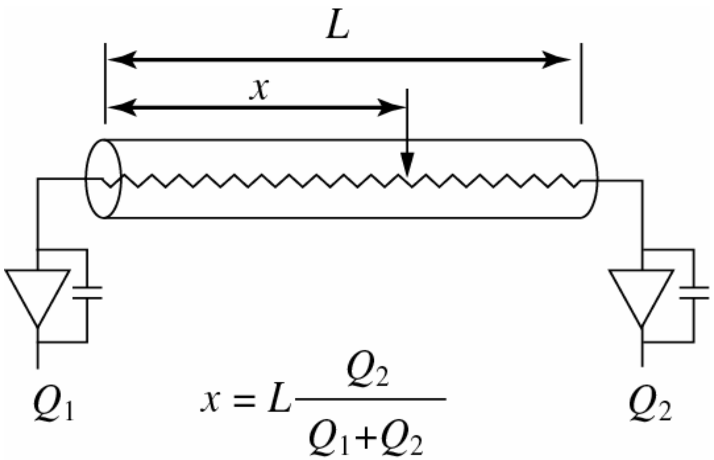
$V_a - V_c = 4.88$ kV



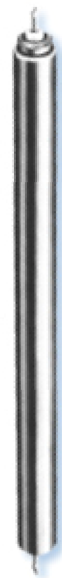
Gas Gain ~ 70

Position Sensitive Proportional Counter Tube

Position sensing using resistive charge division

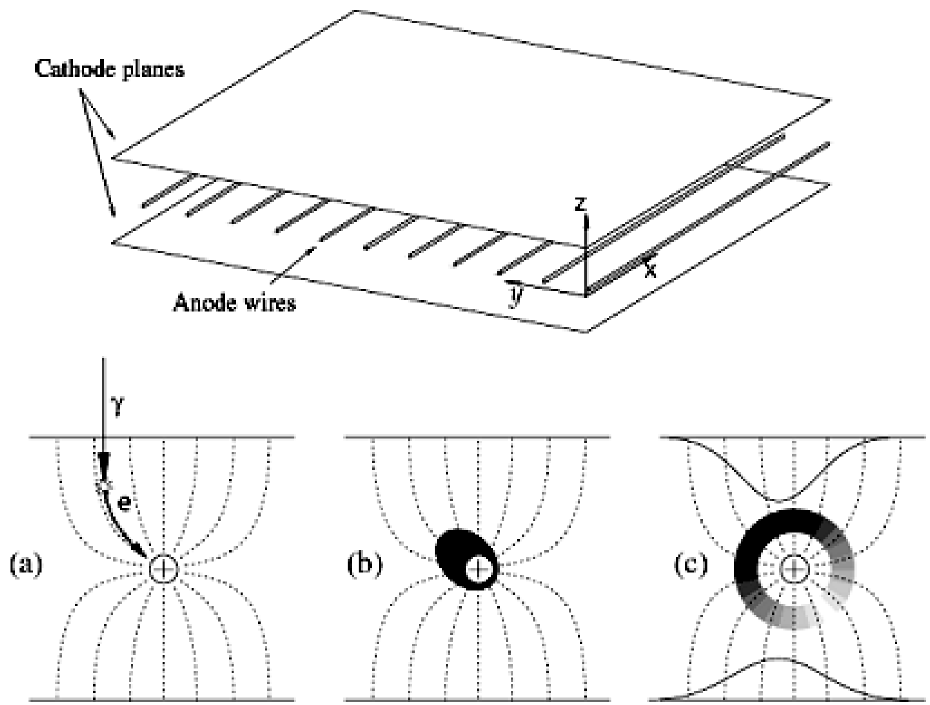


$$x = L\frac{Q_2}{Q_1+Q_2}$$

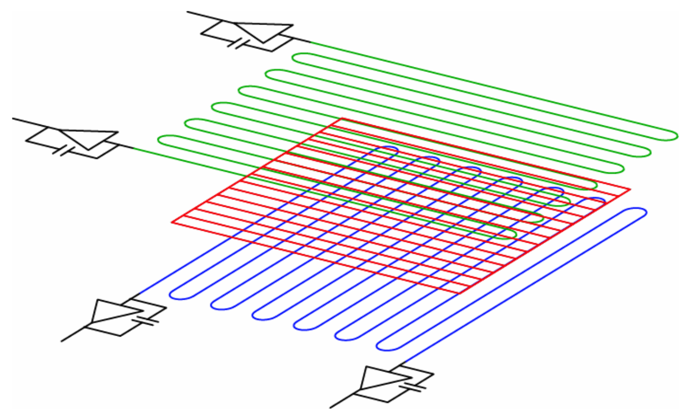


- Simple construction and operation
- Modular design, capable of covering very large areas
- Commercially available, large variety of dimensions

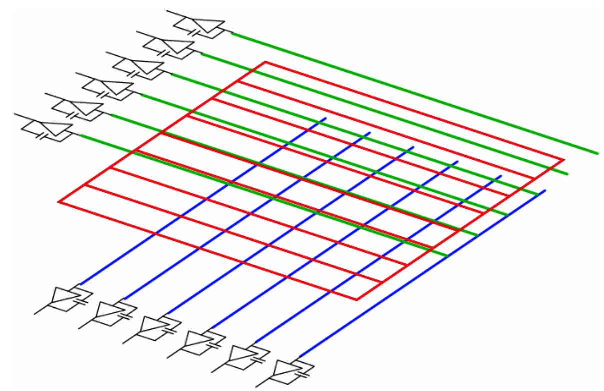
Multi-Wire Proportional Chamber (MWPC)



Global resistive charge division

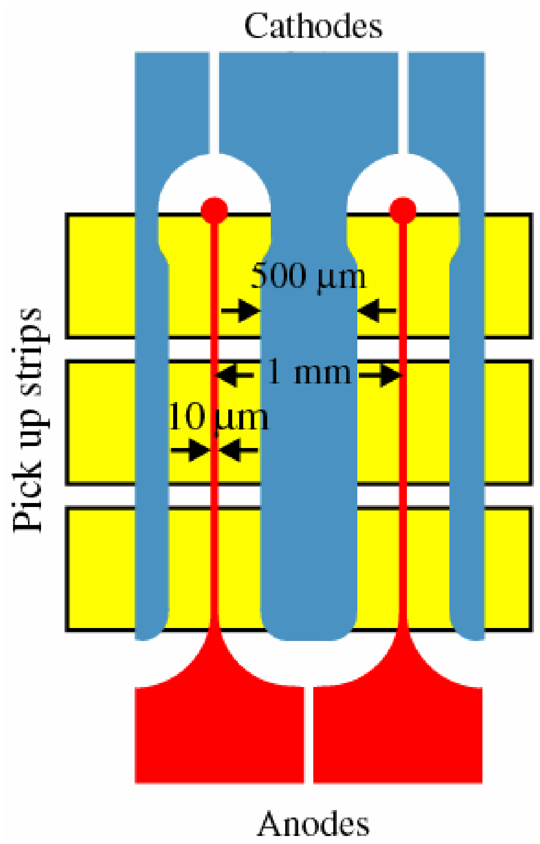


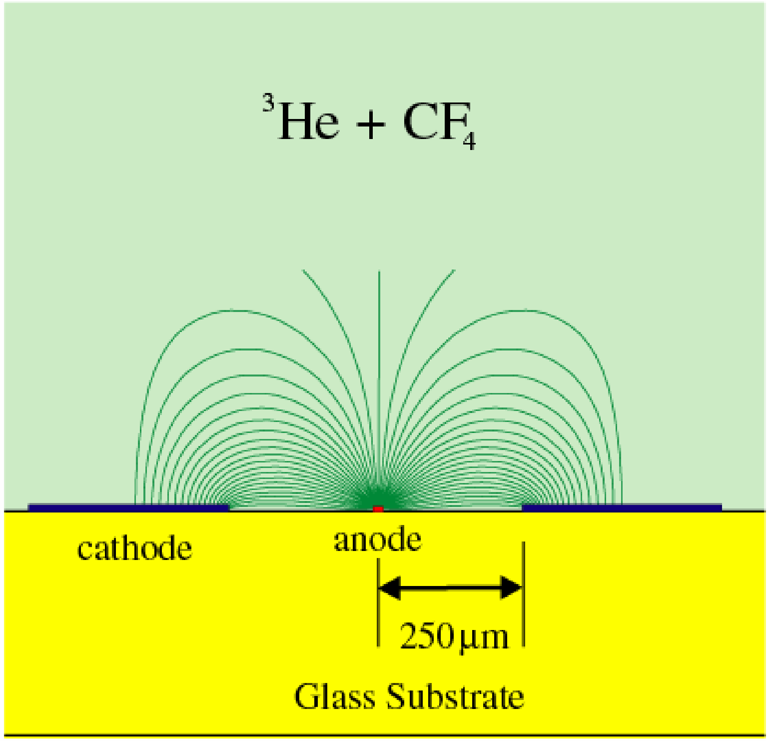
Cross-strip digital readout



- Good Position resolution & rate capability
- Uniform efficiency
- Can be constructed in large area ~m^2
- Flexible position encoding method

Micro-Strip Gas Chamber (MSGC)



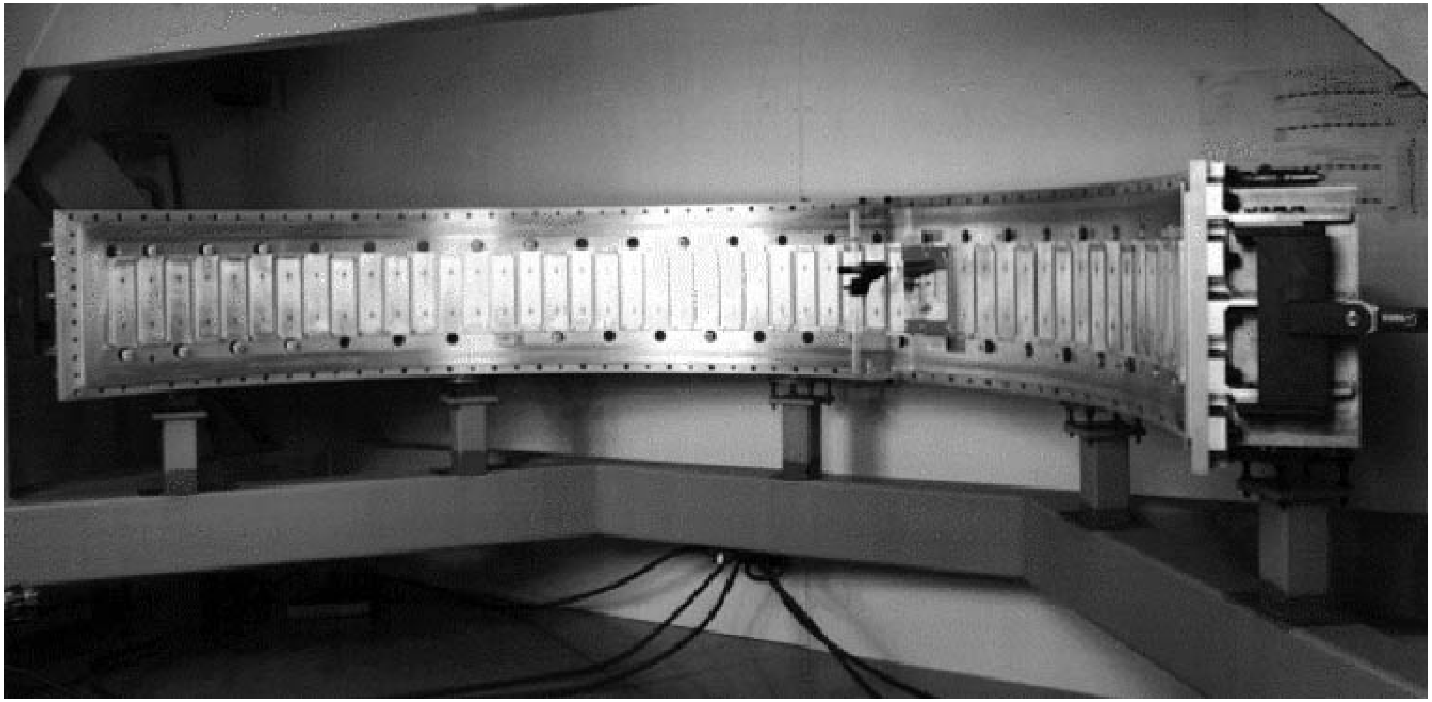


- High rate capability
- Good energy resolution
- Modular construction

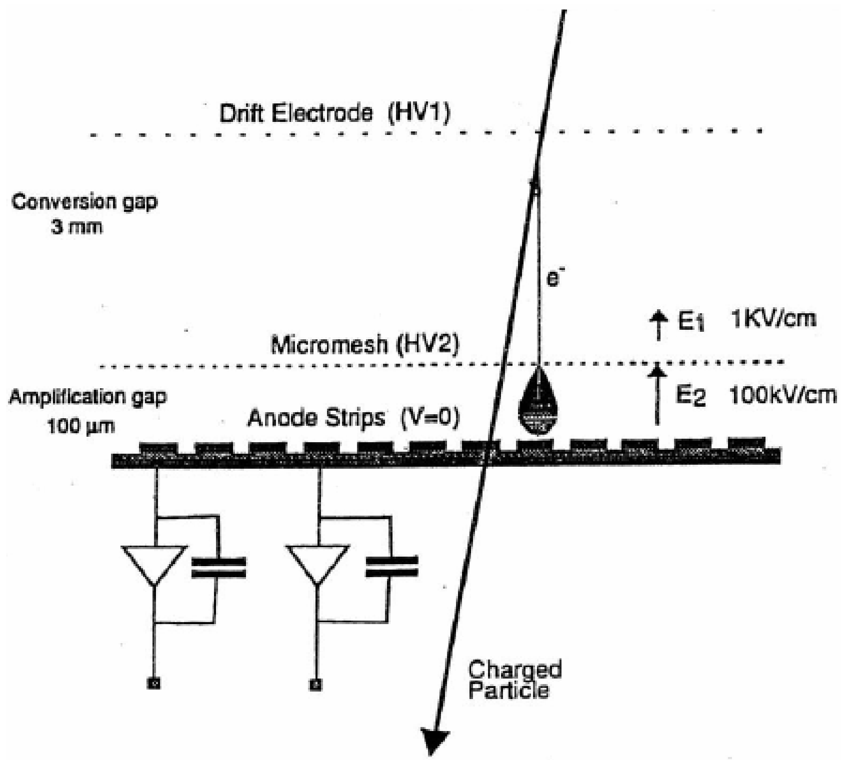
Large Area, Linear Detector with MSGC (ILL)

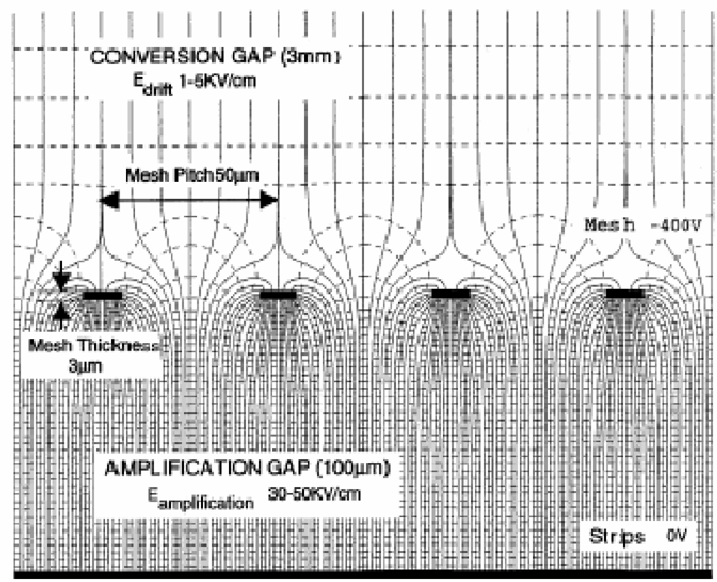
410cm (~154°) x 15cm, 3.1 bars of ^3He + 0.8 bar CF_4. 5.3cm gas depth.

48 MSGC plates with 32 cells each. 50 kcps/cell



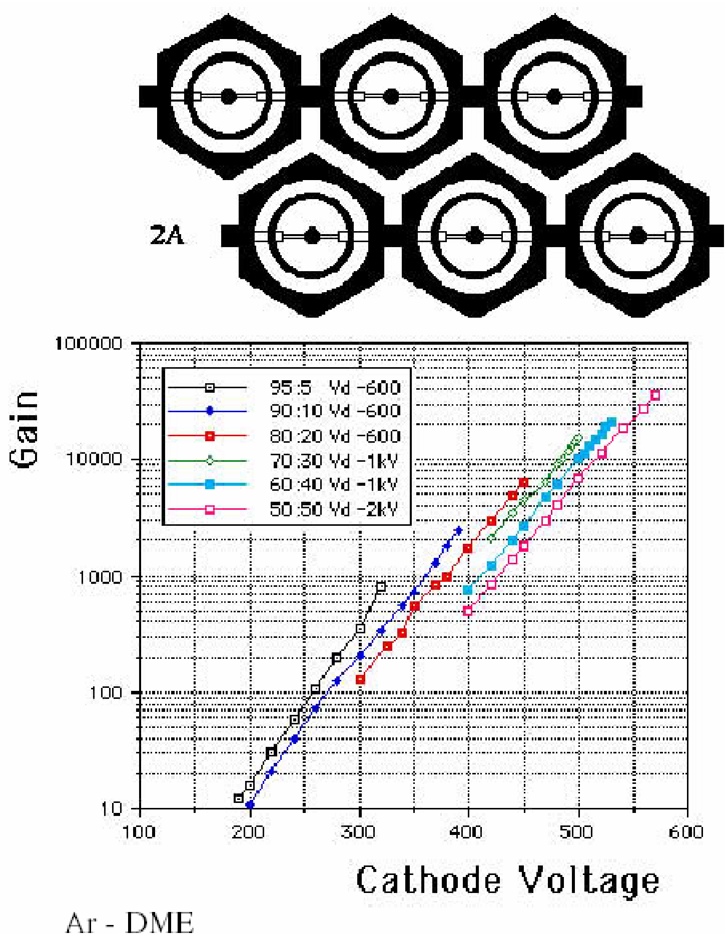
Micro Mesh Gaseous Structure (Micromegas)



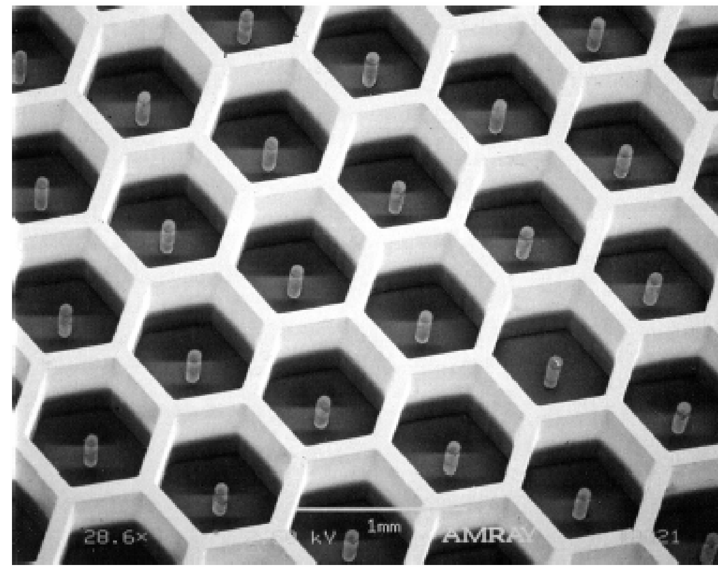


G.Charpak, Y.Giomataris, 1992

Micro Dot / Pin Arrays



S.Biagi, 1993

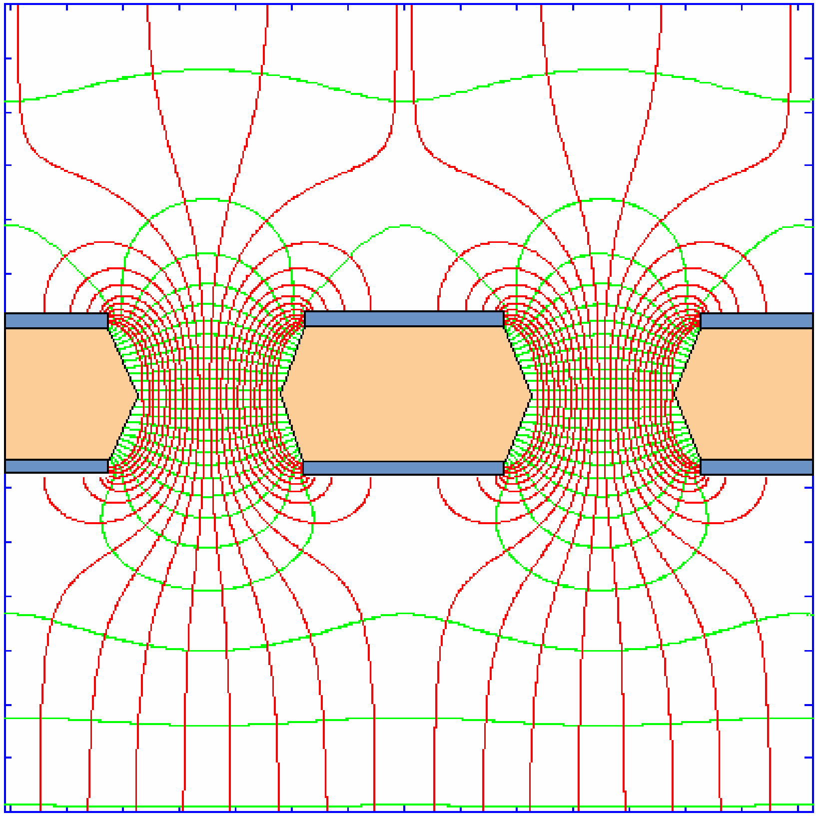


P.Rehak et al 1999

Gas Electron Multiplier (GEM)

F. Sauli, Nucl. Instrum. Methods A386(1997)531

Thin metal-coated polymer foil chemically pierced by a high density of holes.



Typical dimensions:

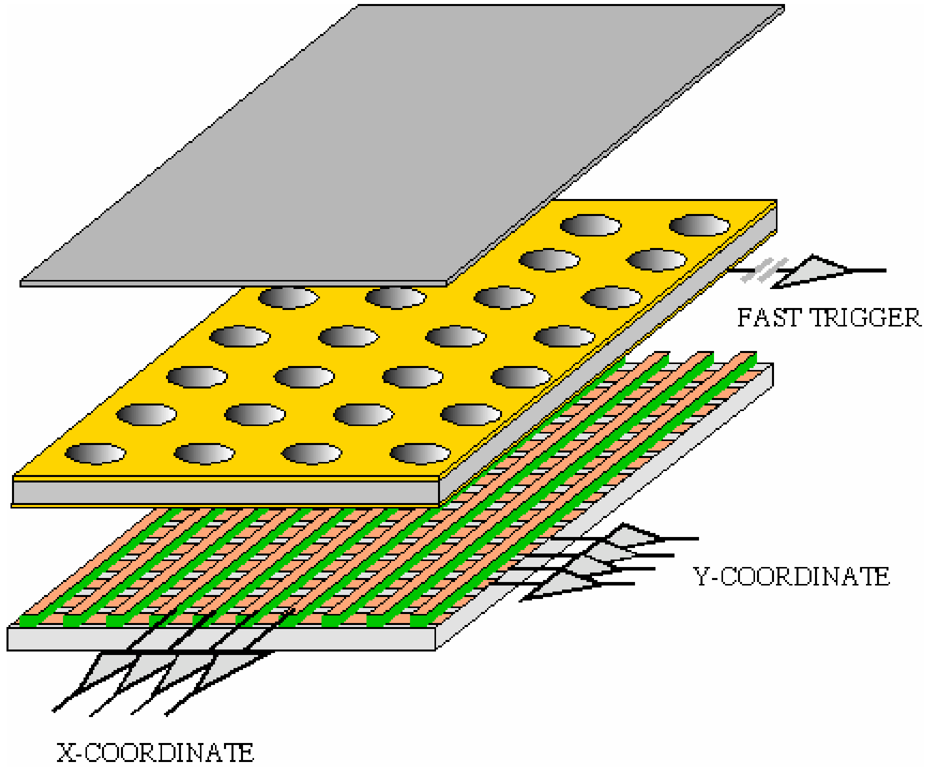
- 50μm thick Kapton foil
- 5μm thick copper coatings
- 80μm diameter holes
- 140μm hole pitch

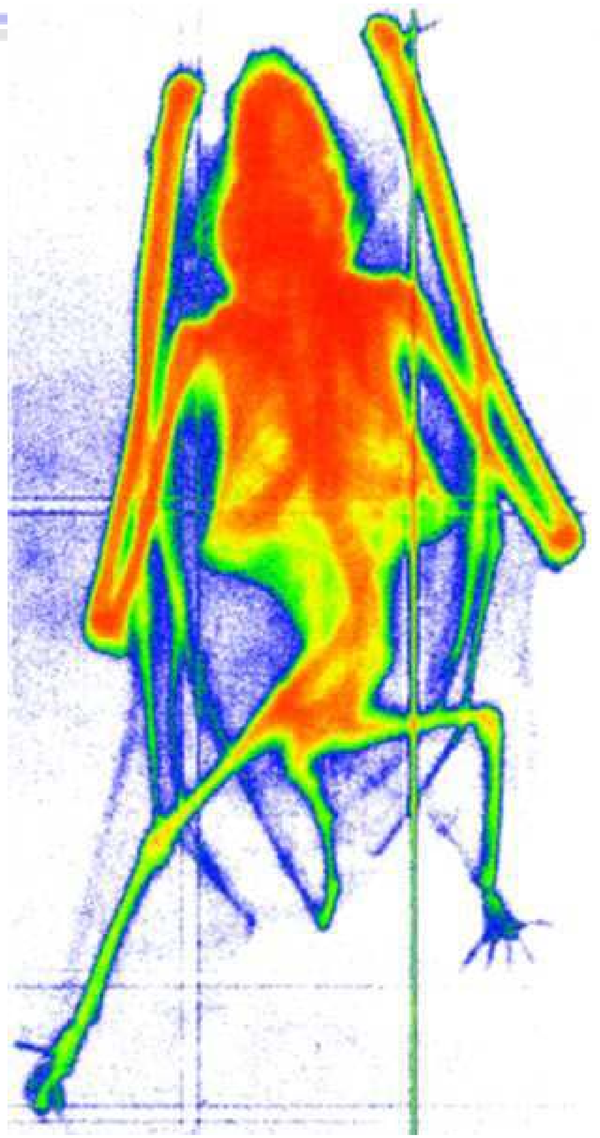
On application of a voltage gradient, electrons released on the top side drift into the hole, multiply in avalanche and transfer to the other side.

Proportional gains above 10^3 are obtained in most common gases.

X-ray Imaging, Using GEM

Using the lower GEM signal, the readout can be self-triggered with energy discrimination:



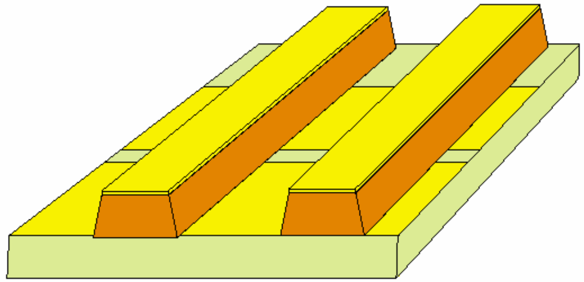


A. Bressan et al, Nucl. Instr. and Meth. A 425(1999)254
F. Sauli, Nucl. Instr. and Meth.A 461(2001)47

9 keV absorption radiography of a bat (image size ~ 60 x 30 mm²)

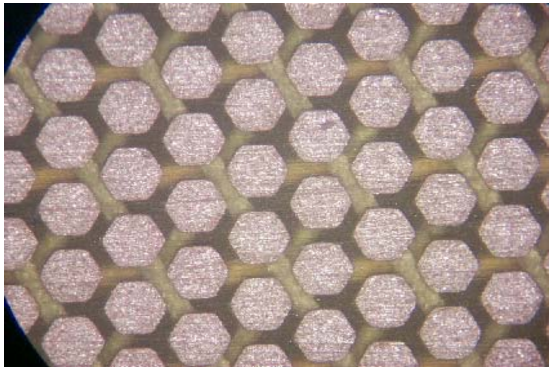
2D Readout of GEMs

Cross Strips

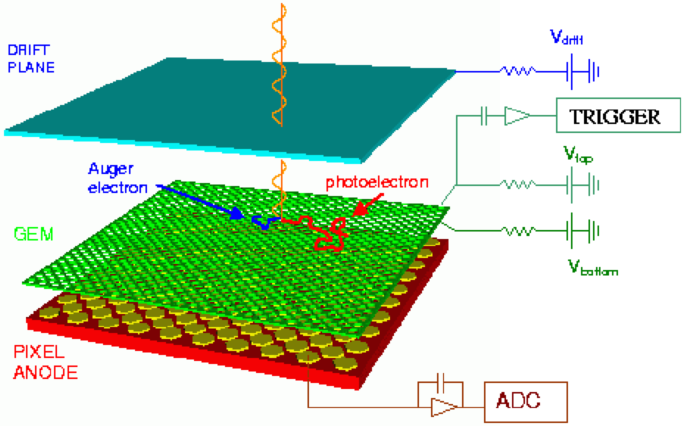


A. Bressan et al, Nucl. Instr. and Meth. A425(1999)254

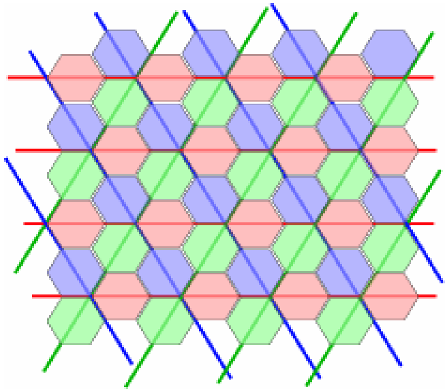
Strip Pixel
(3 sets of strips to resolve multiple hits)

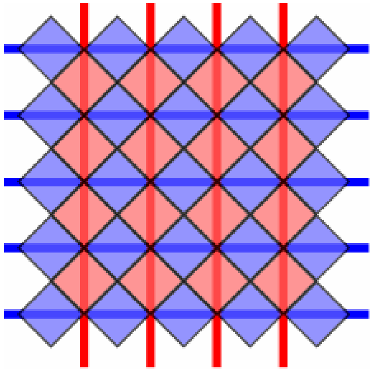


True Pixel Readout



R. Bellazzini et al Nucl. Instr. and Meth. A478 (2002) 13

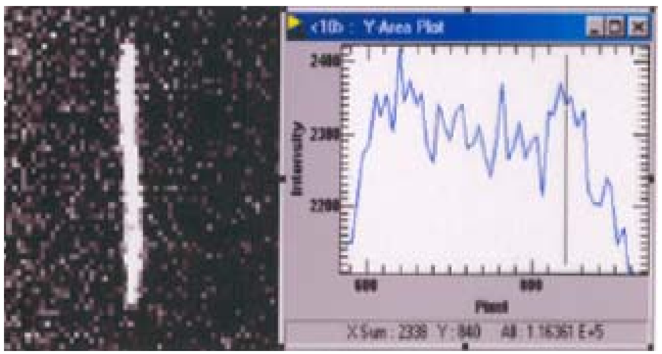


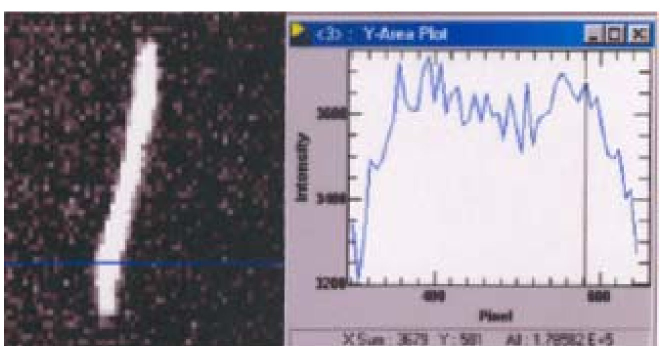


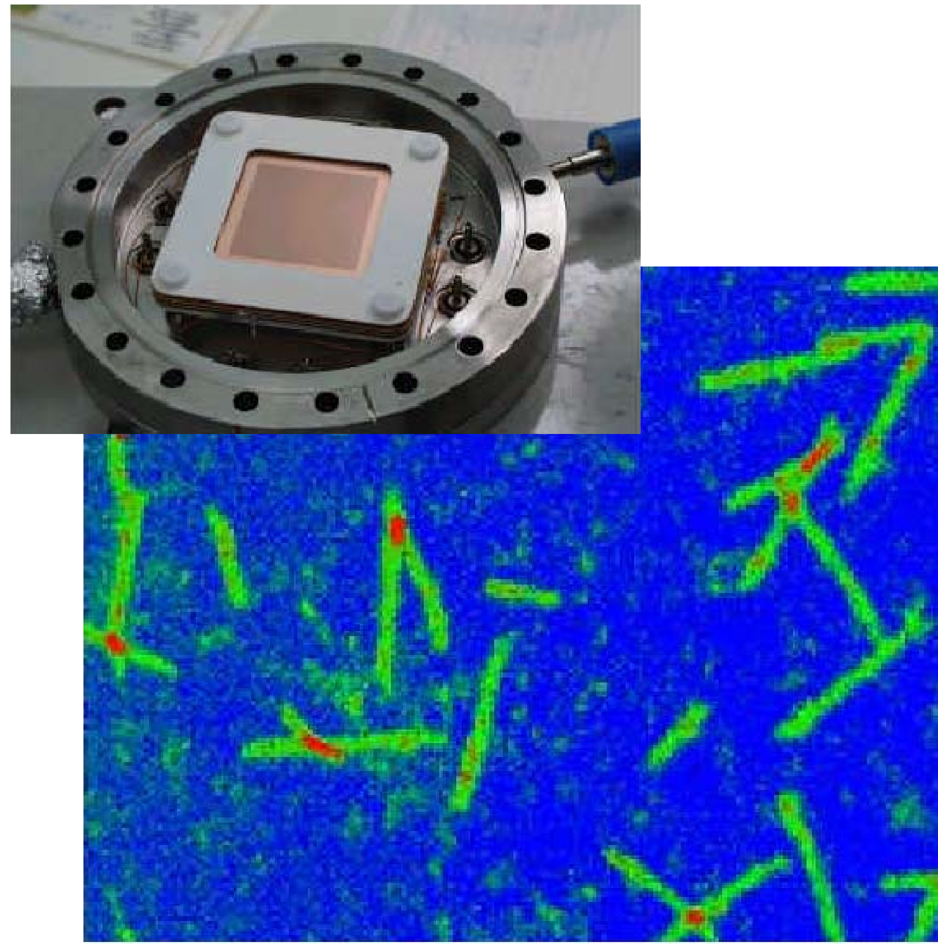
A. Bressan et al, Nucl. Instr. and Meth. A425(1999)254

Optical Imaging of the p/^{3}H Tracks with GEM

Use a CCD camera to record the scintillation light emitted from the GEM holes during the electron multiplication process.







F.A.F. Fraga et al, Nucl. Instr. and Meth. A478 (2002) 357

Active Matrix Readout with ^3He?

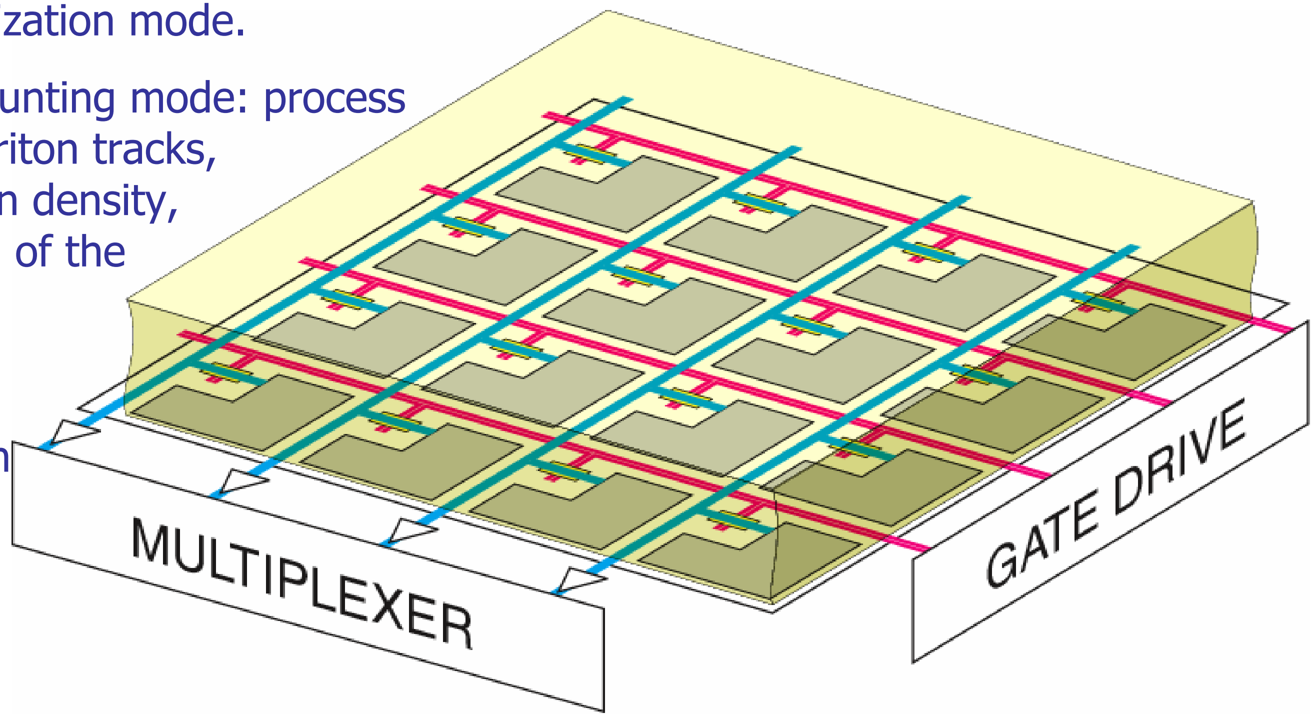
A-Si Flat Panel Active Matrix Readout has been gaining popularity in the field of medical imaging. Each pixel is basically a capacitor that integrates charge over a period of time, and then being read out sequentially along each columns.

Panel size: 30cmx30cm, pixel size: 100µm, frame rate: kHz.

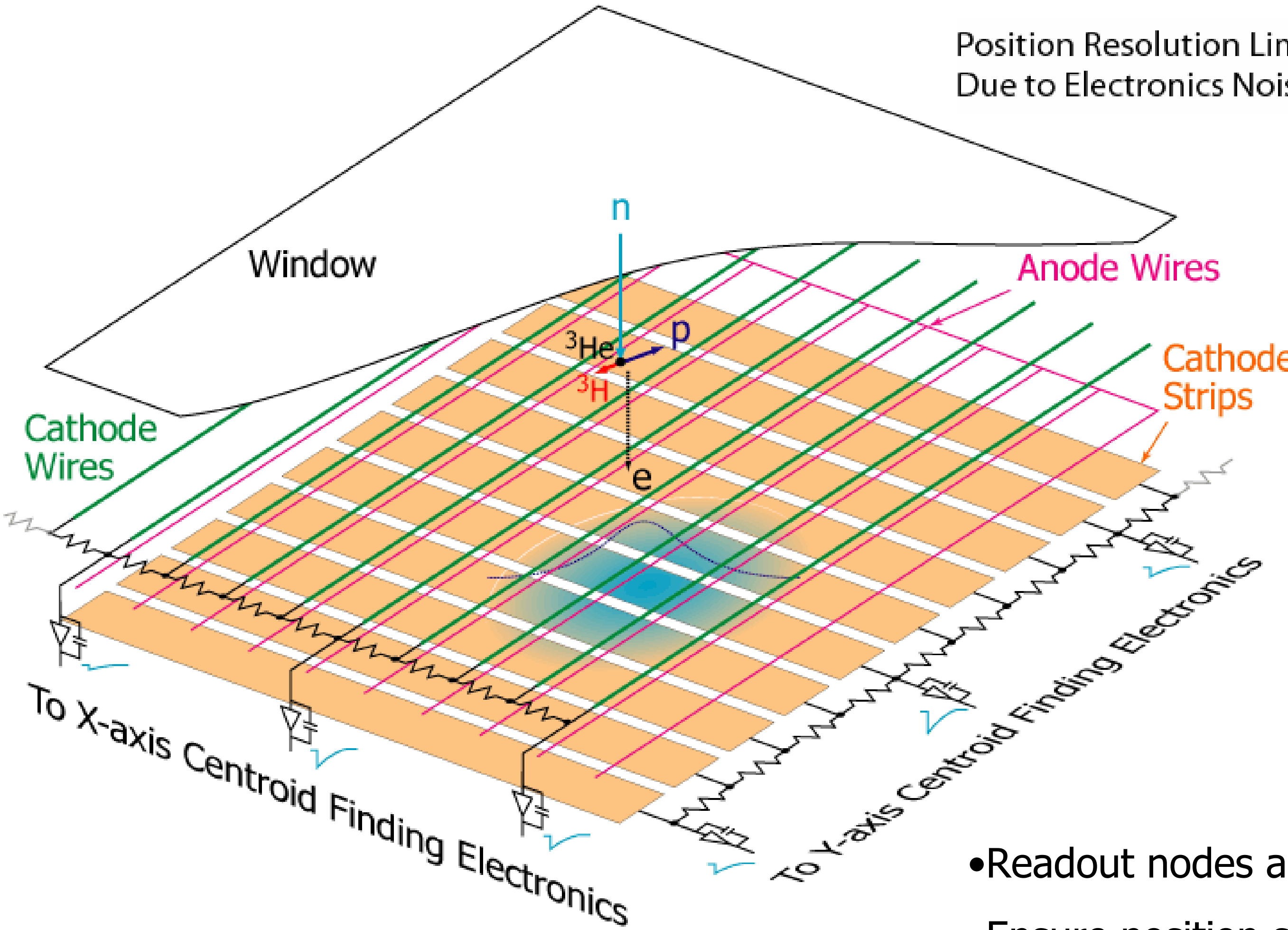
This active matrix can be used as the anode plane of a GEM chamber or an ionization chamber.

•Operating in integration mode at extreme high rate conditions. Reduced gamma rejection. Ionization mode.

•Operating in semi-counting mode: process the image of proton/triton tracks, analyze their ionization density, and identify the origin of the projectiles.
Medium-low rate,
very high resolution,
good gamma rejection



Position Encoding with Interpolating Cathode Strips

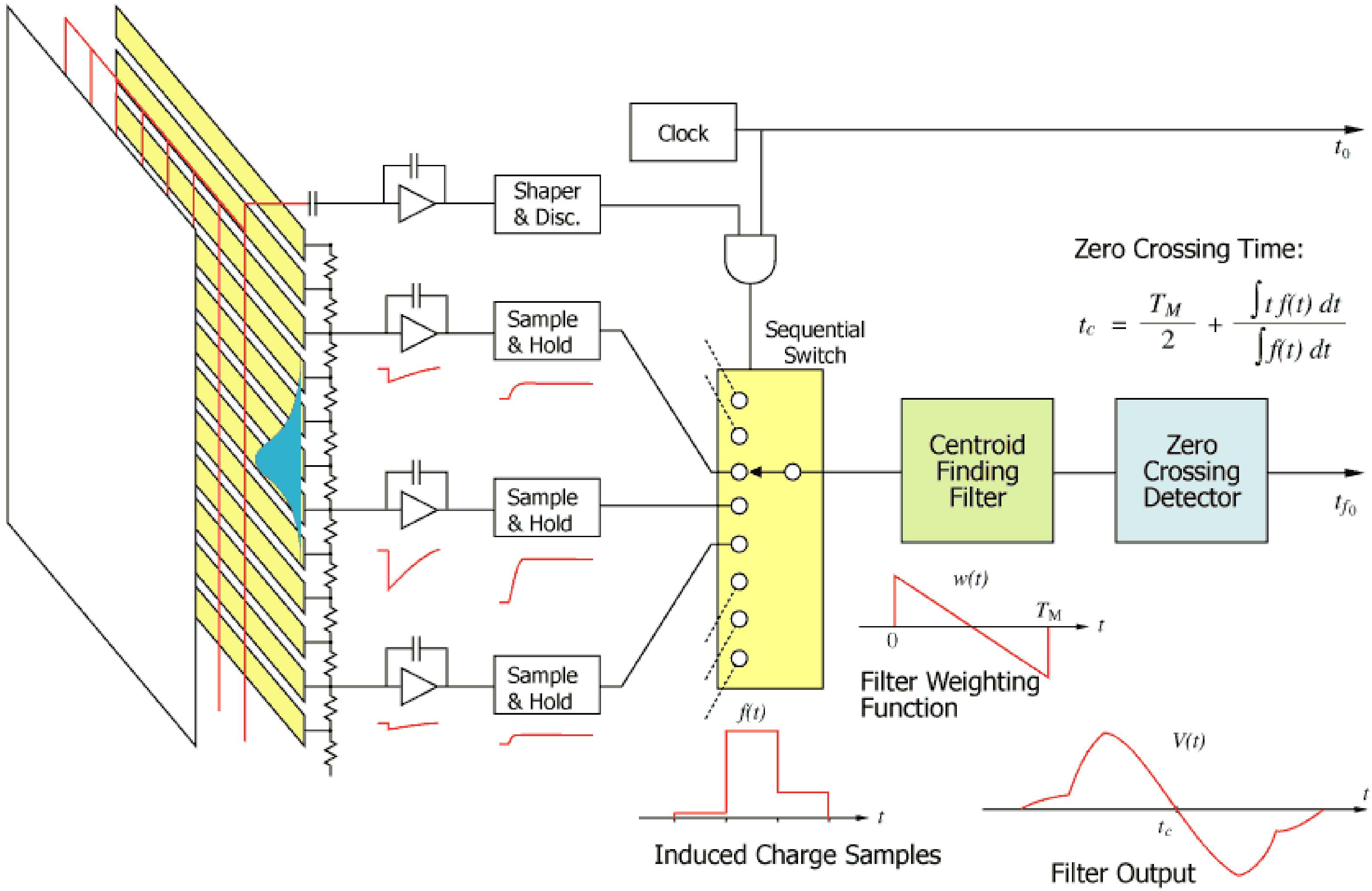


Position Resolution Limit Due to Electronics Noise $\propto \dfrac{C_D^{1/2}}{Q_S} \dfrac{L}{N^{3/2}}$

- Readout nodes act as fiducial marks
- Ensure position stability
- Greatly reduces signal to noise requirement

J.L. Alberi and V. Radeka, IEEE Trans. Nucl. Sci. NS-23 (1976) 251
V. Radeka and R.A. Boie, Nucl. Instrum. & Meth. 178 (1980) 543-554

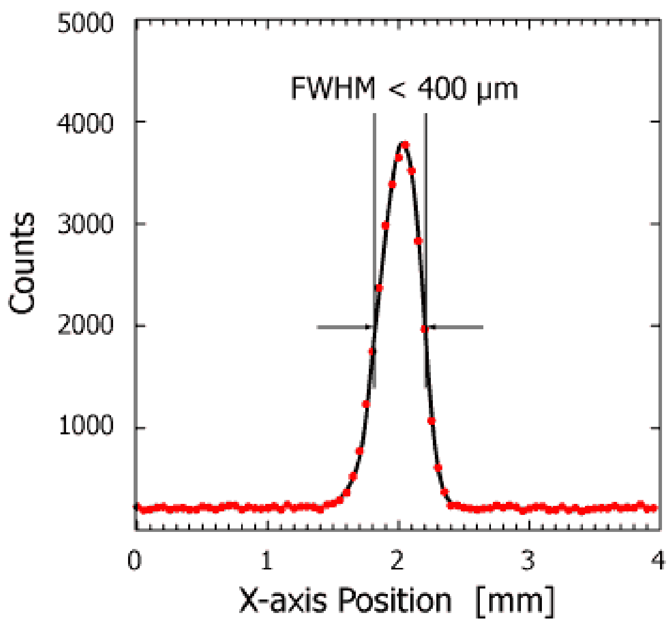
Analog Centroid Finding System



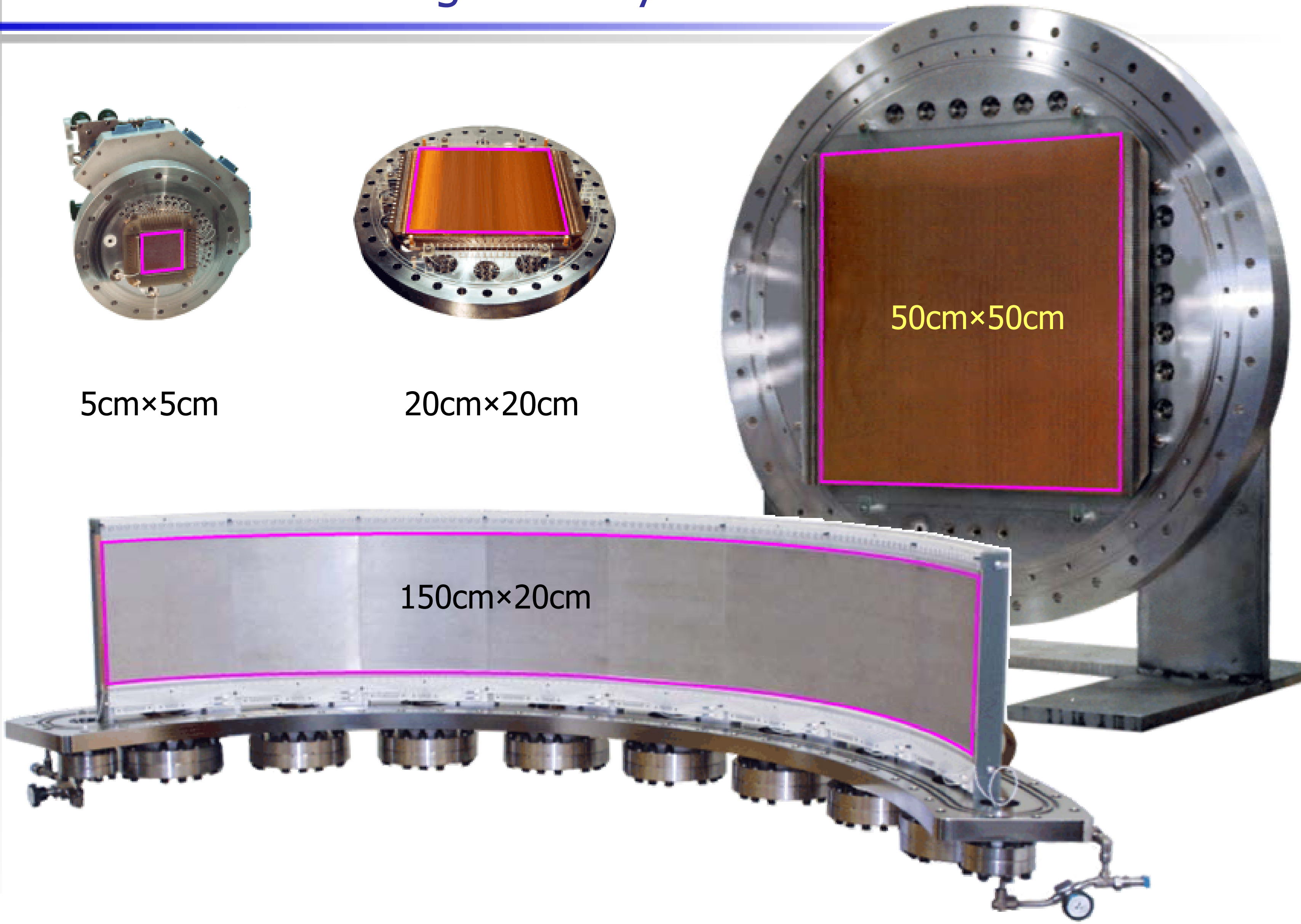
V. Radeka and R.A. Boie, Nucl. Instrum. & Meth. 178 (1980) 543-554

High Precision 5cm×5cm Detector

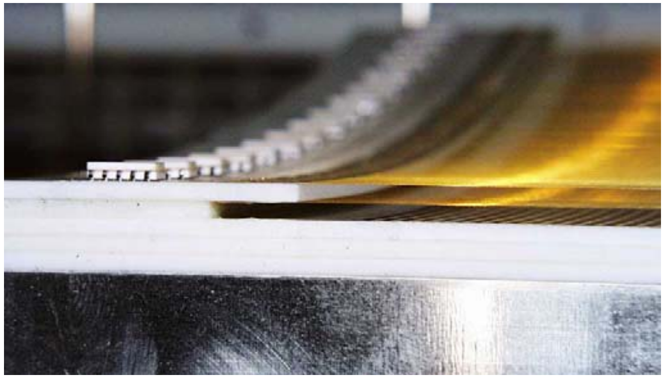
- Developed for fluid dynamics, radiography
- 8 atm. ^3He + 6 atm. propane
- Best neutron position resolution to date in a ^3He gas detector

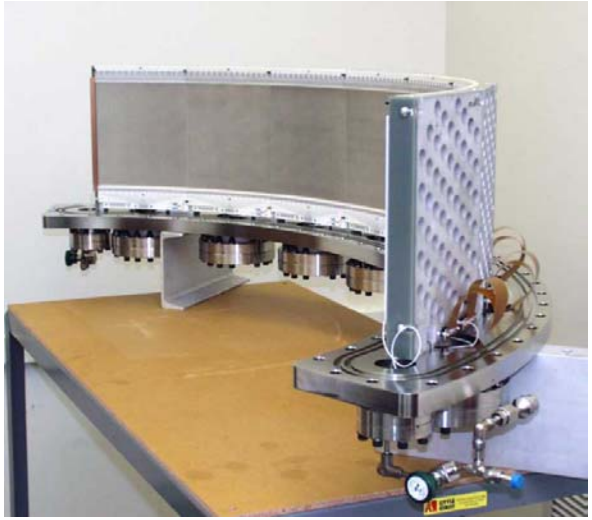


BNL's Neutron Imager Family



120º Two-Dimensional Thermal Neutron Detector for Protein Crystallography



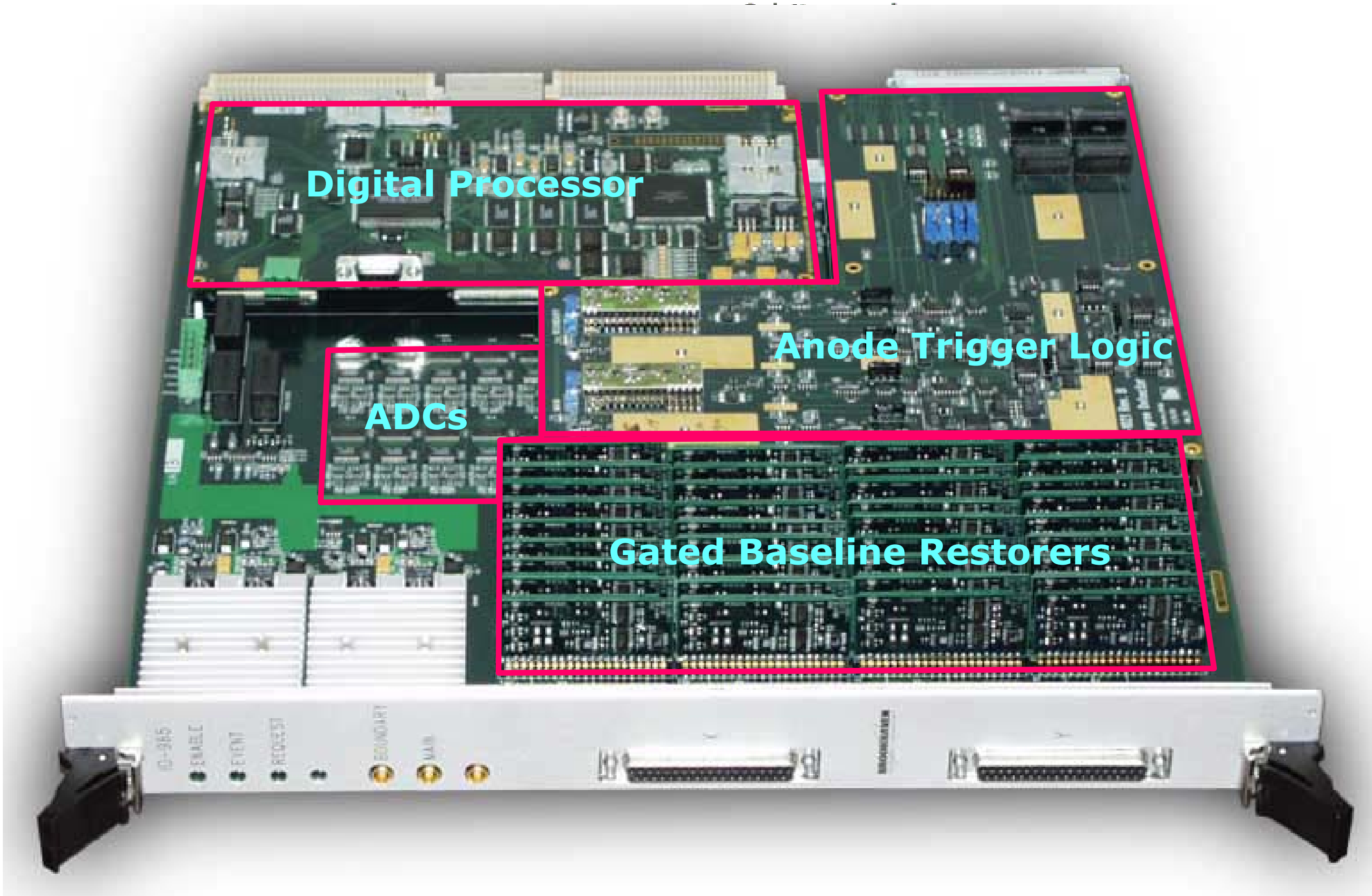


J. Fried et al., Nucl. Instrum. & Meth. 478 (2002) pp. 415-419

New Digital Centroid Finding Module

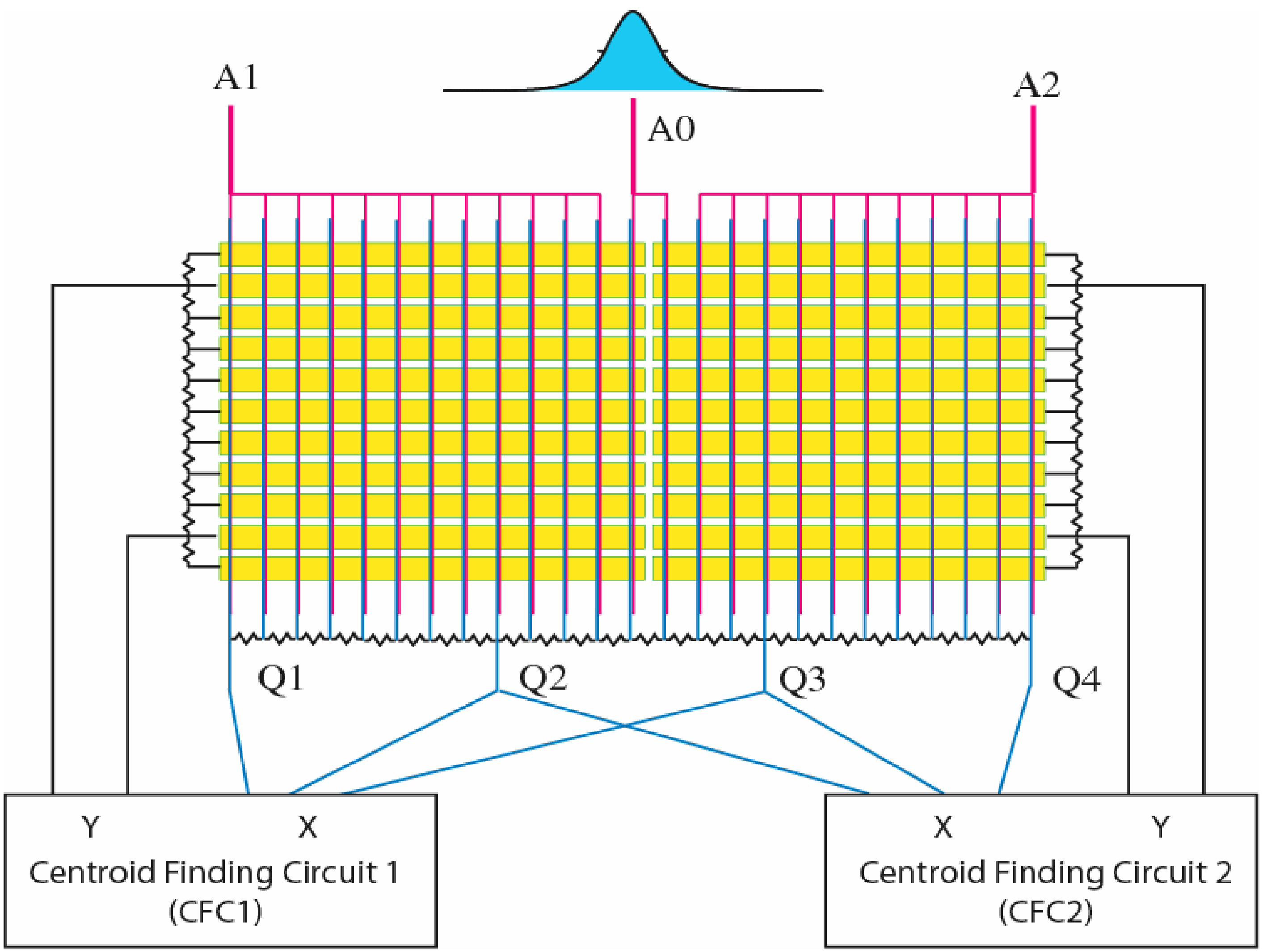
Interconnects to

X-Y output



Preamp outputs from the detector (segment)

Seamless Boundaries



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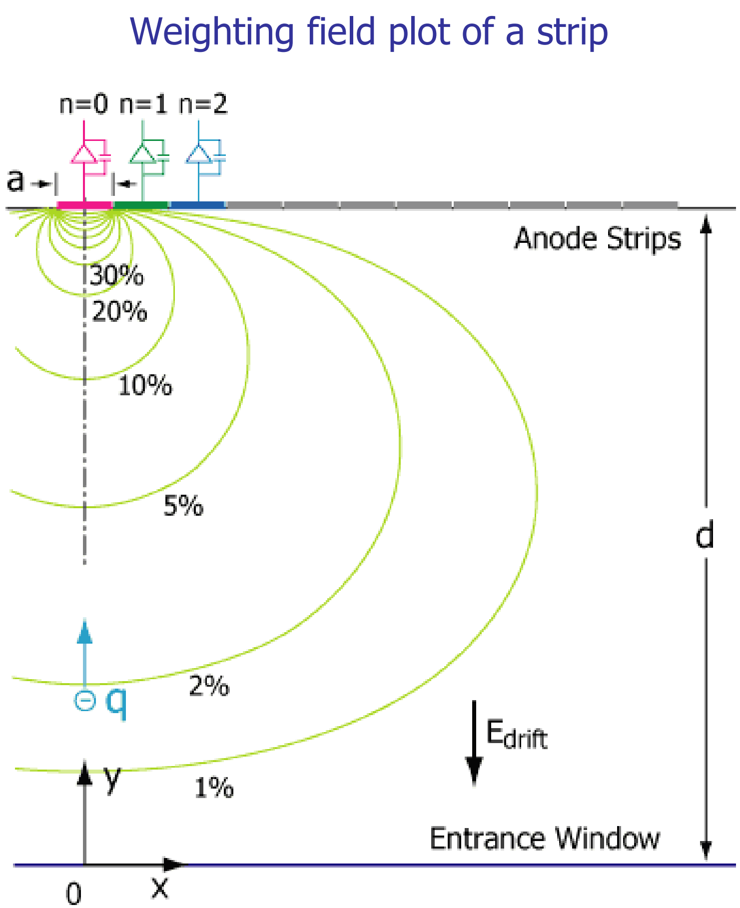
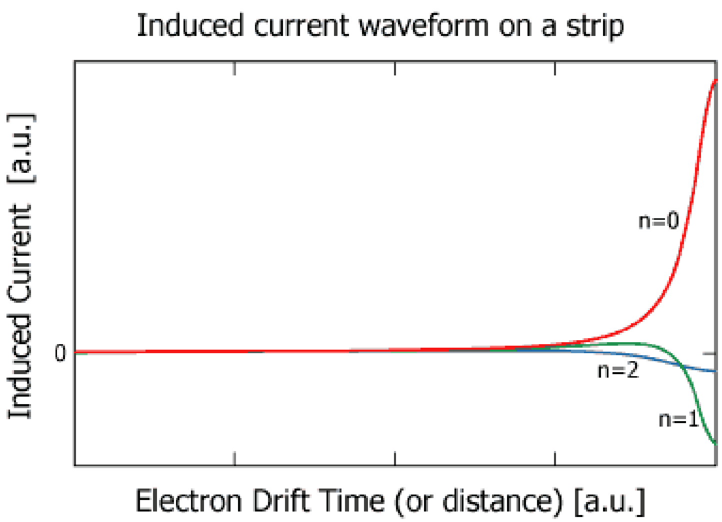
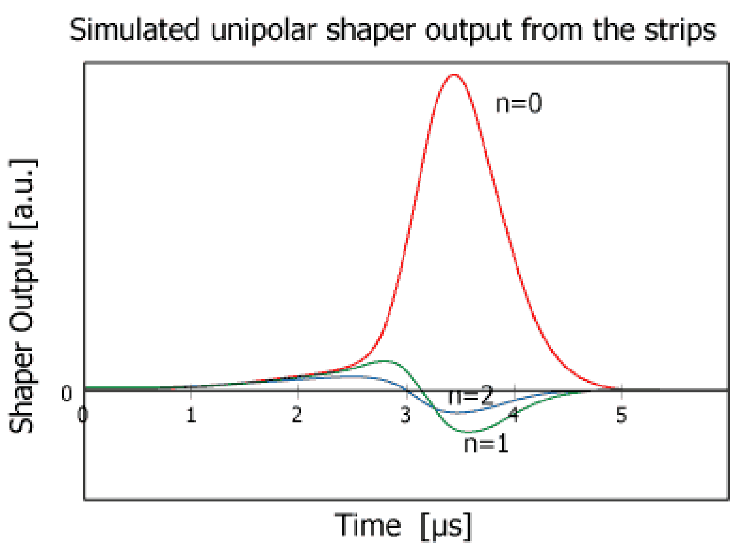
J. Fried et al., Nucl. Instrum. & Meth. 478 (2002) pp. 415-419

One-Dimensional Ionization Chamber

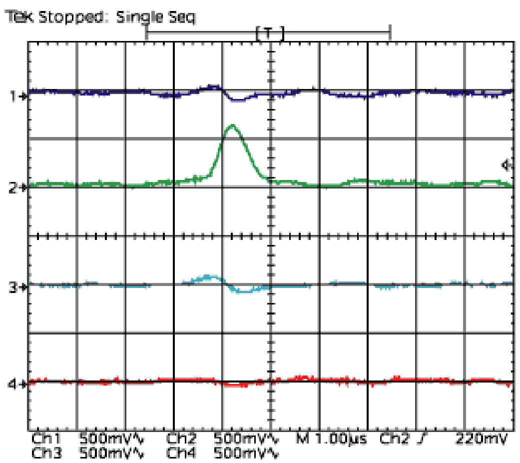


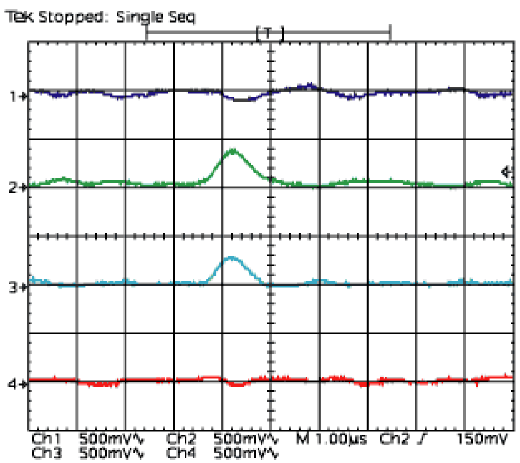




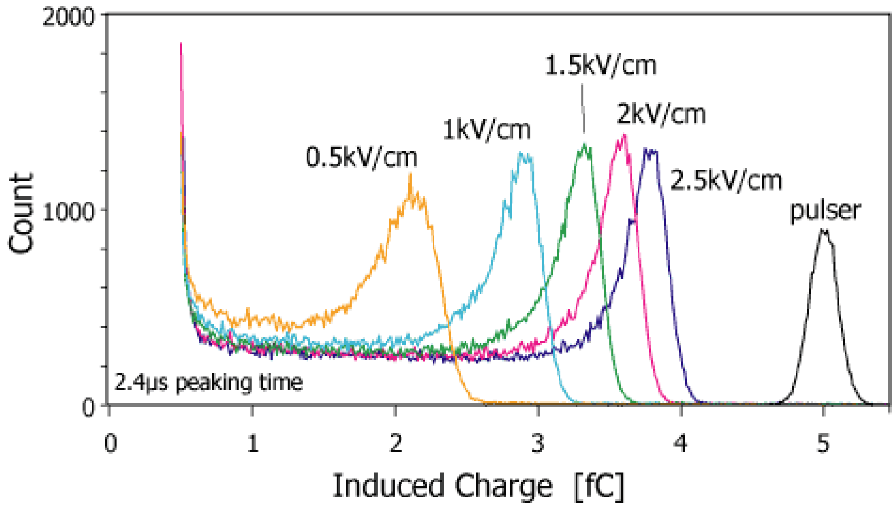
B. Yu et al, IEEE Trans. On Nucl. Sci. vol. 48 (2001) 336-340

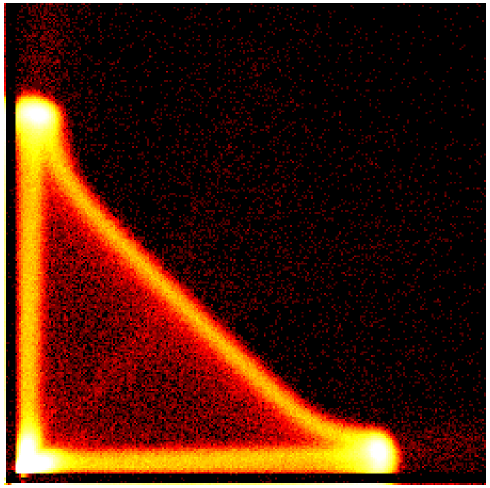
One-Dimensional Ionization Chamber





Pulse height distribution as a function of drift field

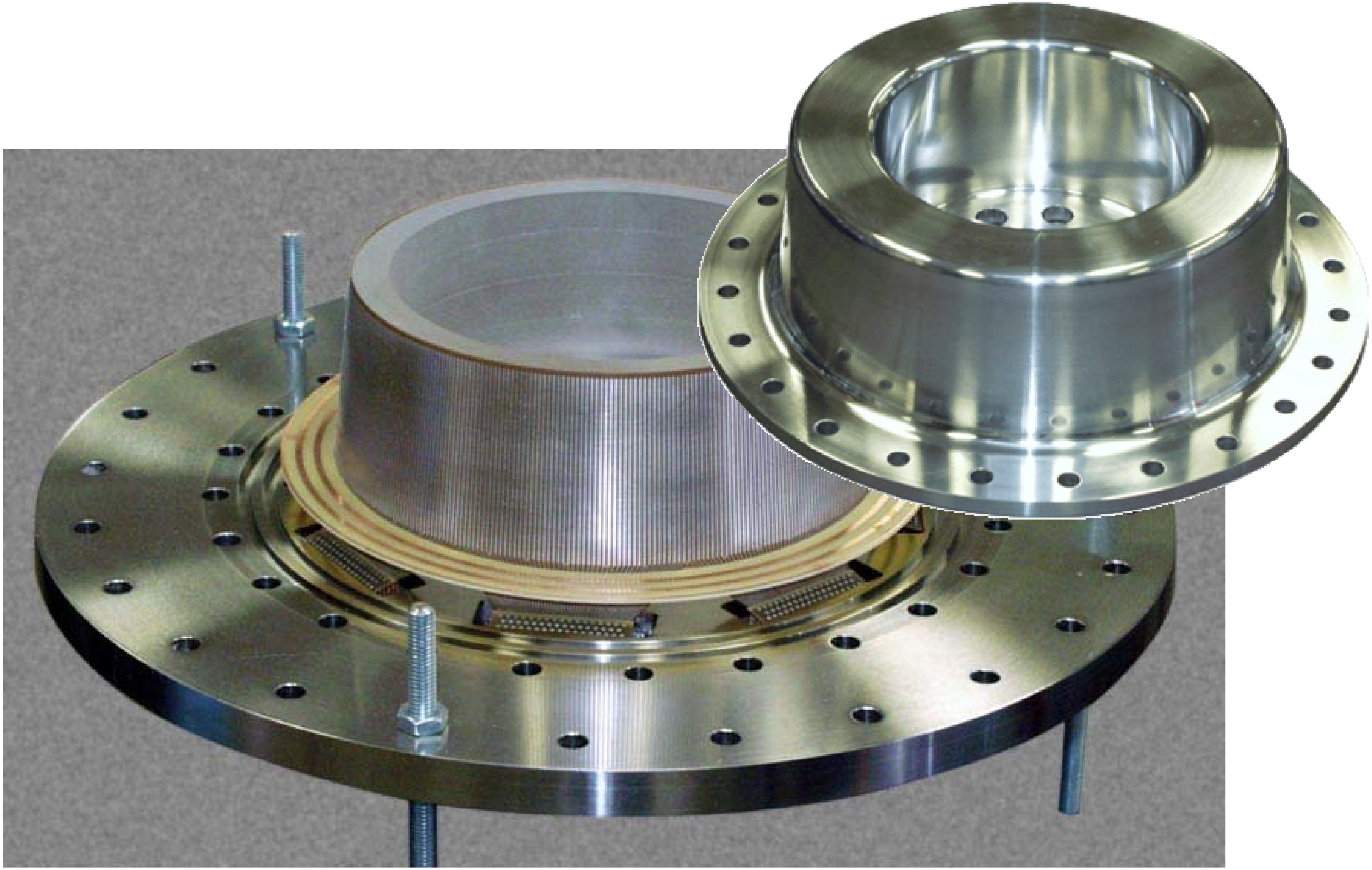




Pulse height correlation between two adjacent strips

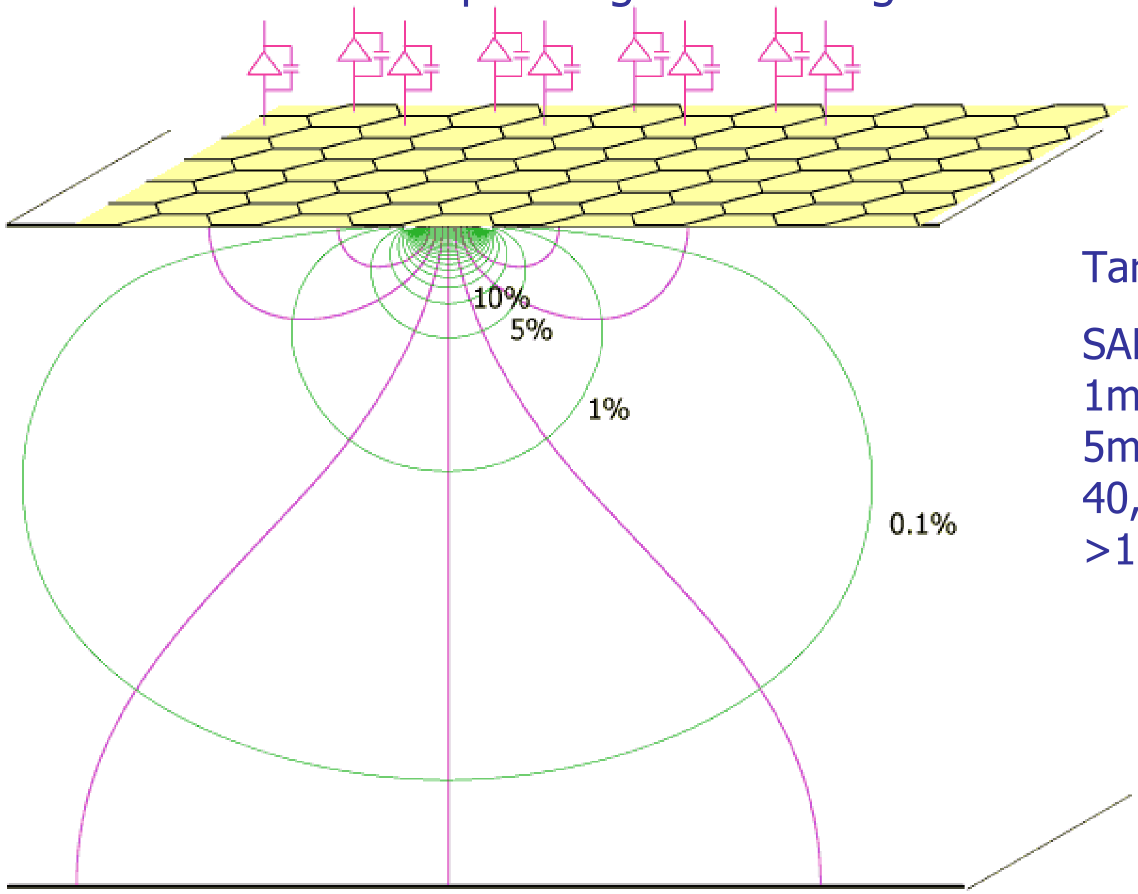
B. Yu et al, IEEE Trans. On Nucl. Sci. vol. 48 (2001) 336-340

One-Dimensional Ionization Chamber for Crystal Backscattering Experiment



2D Pixel Readout in Ionization Mode

Each pixel is connected to its own preamp/shaper/multi-level discriminator circuit operating inside the gas enclosure

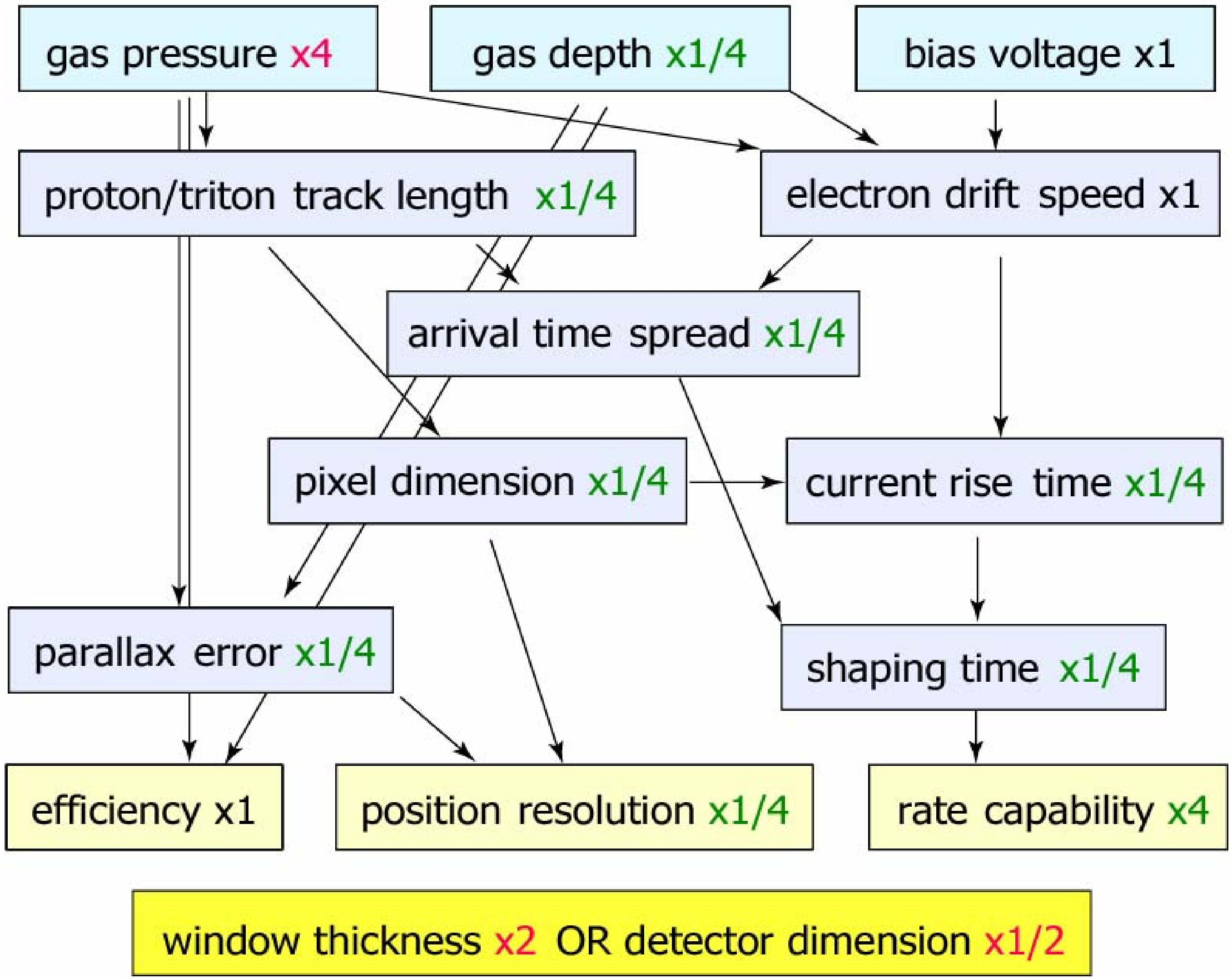


Target application:

SANS:
1mx1m area,
5mm position resolution,
40,000 channels,
$>10^7$ /s rate

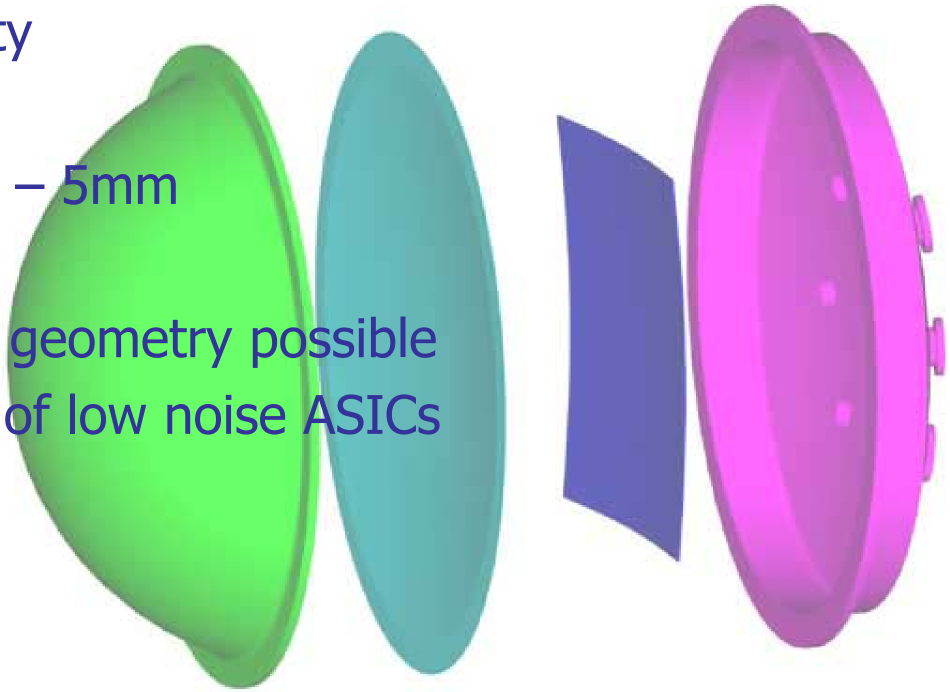
Scaling of the Ionization Chamber

Assume the gas mixtures remains the same. So is the bias voltage for the drift field.

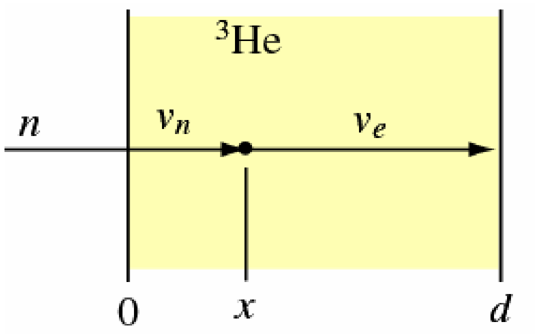


2D Pixel Readout in Ionization Mode

- Ultra high count rate capability:
  $\sim 10^5$ /s per pixel, $>10^8$ /s per detector
- No gas amplification:
  - No aging effect
  - Stability and reliability
- Flexible geometry:
  - Pixel dimension: ~ 1 – 5mm
  - Parallax reduction
  - Large area, complex geometry possible
- Reliant on development of low noise ASICs



Timing Resolution in a Planar Detector



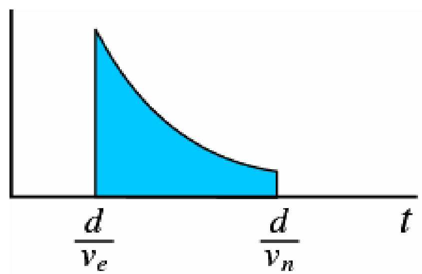
d is the total thickness of the gas volume

x is the distance of the interaction point to the entrance window

v_n is the neutron velocity (~ mm/μs)

v_e is the electron drift velocity (~ cm/μs)

L is the neutron absorption length



The arrival time distribution of netrons of a given energy has the form of (assume $v_e > v_n$):

$$g(t) = e^{-\frac{t-t_0}{\tau}} \qquad t_0 = \frac{d}{v_e} \qquad \tau = L\left(\frac{1}{v_n} - \frac{1}{v_e}\right)$$

One extreme case is that the absorption of neutron is uniform:

$$\sigma_t = \frac{d}{\sqrt{12}}\left(\frac{1}{v_n} - \frac{1}{v_e}\right)$$

for example: 1Å, 1cm gas gives ~ 0.4μs

The other extreme case is that all neutrons are absorbed in the gas volume.

$$\sigma_t = L\left(\frac{1}{v_n} - \frac{1}{v_e}\right)$$

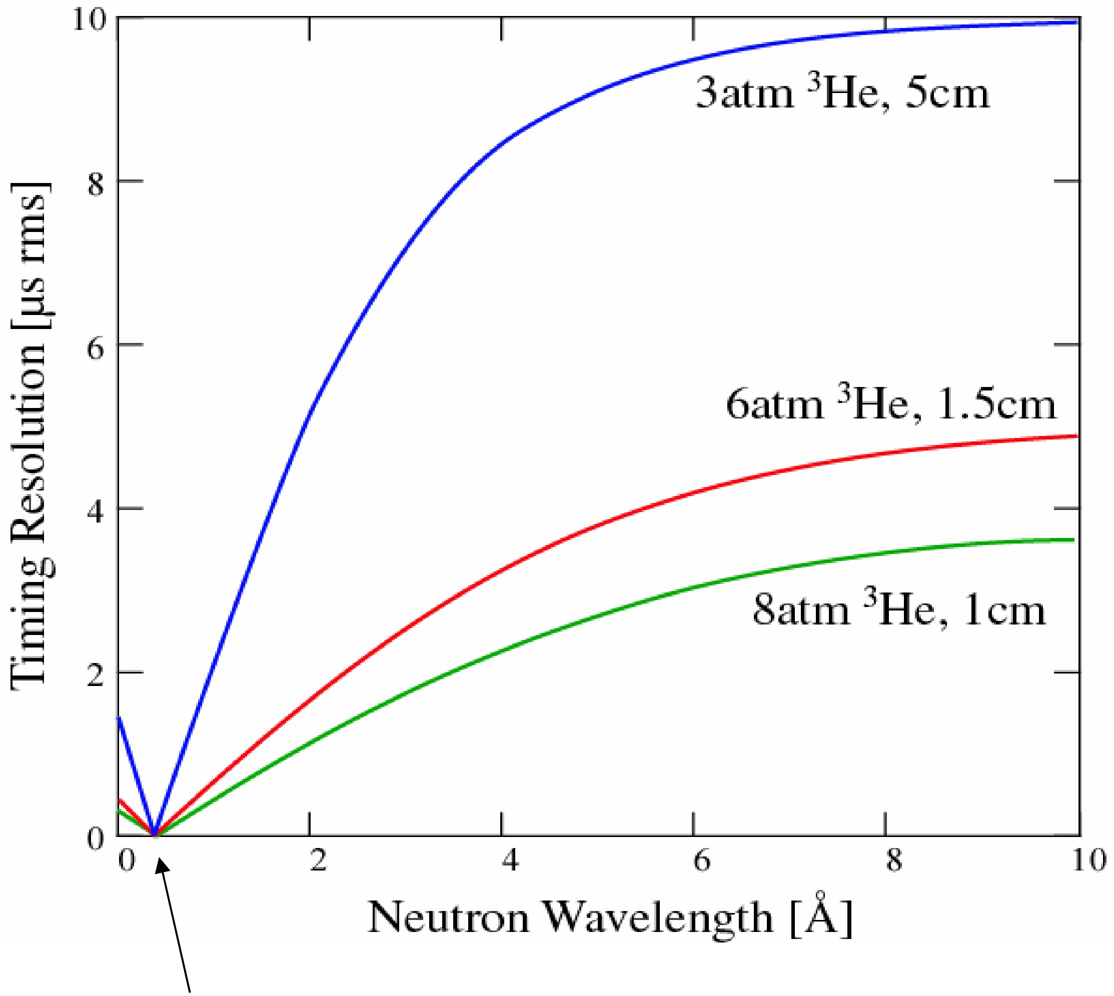
In fact. if we neglect the electron drift velocity:

$$\sigma_t \sim \frac{L}{v_n} \sim \frac{31}{P} \quad (\mu s)$$

P is the ^{3}He pressure (atm)

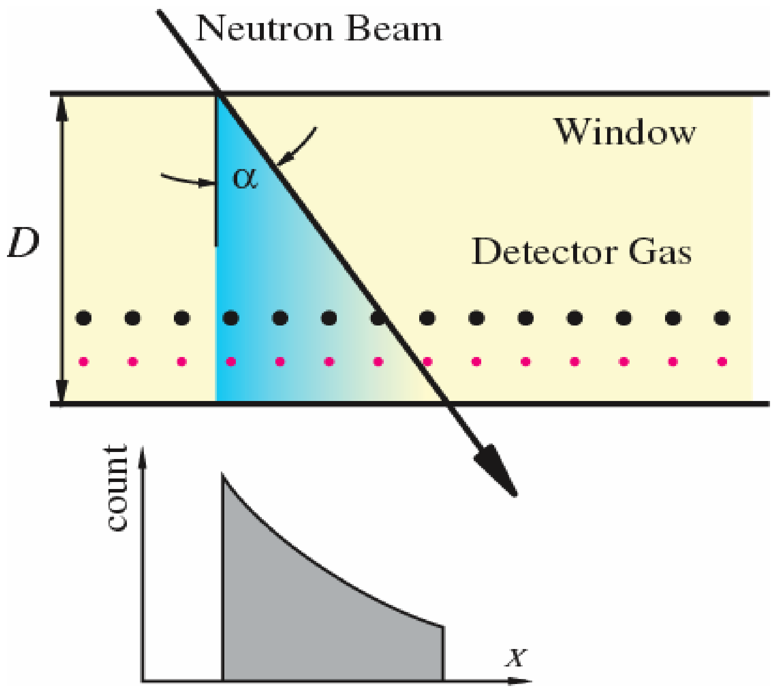
for example: 10Å, 2atm, 4cm gas gives ~ 15μs

Timing Resolution in a Planar Detector



The electron drift velocity is set to be 1cm/μs, which matches the neutron speed at this energy.

Parallax Error In a Gas Detector



The rms error due to parallax is:

$$\sigma = \frac{L \sin\alpha}{1 - e^{-A}} \sqrt{e^{-2A} - e^{-A}(A^2 + 2) + 1}$$

where:

$$A = \frac{D}{L \cos\alpha}$$

L is the neutron absorption length in the gas

Two extreme cases : (all other cases lies in between these two)

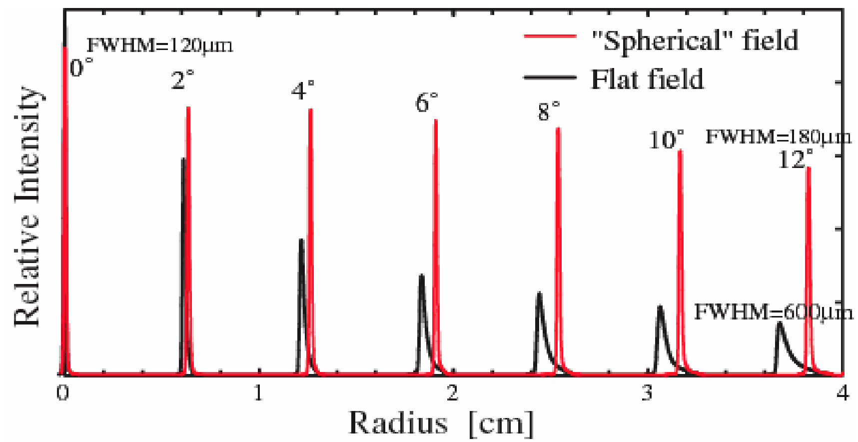
1. D << L: (low 3He pressure, fast neutrons, thin gas depth…) $\quad \sigma = \dfrac{D \cdot \tan\alpha}{\sqrt{12}}$

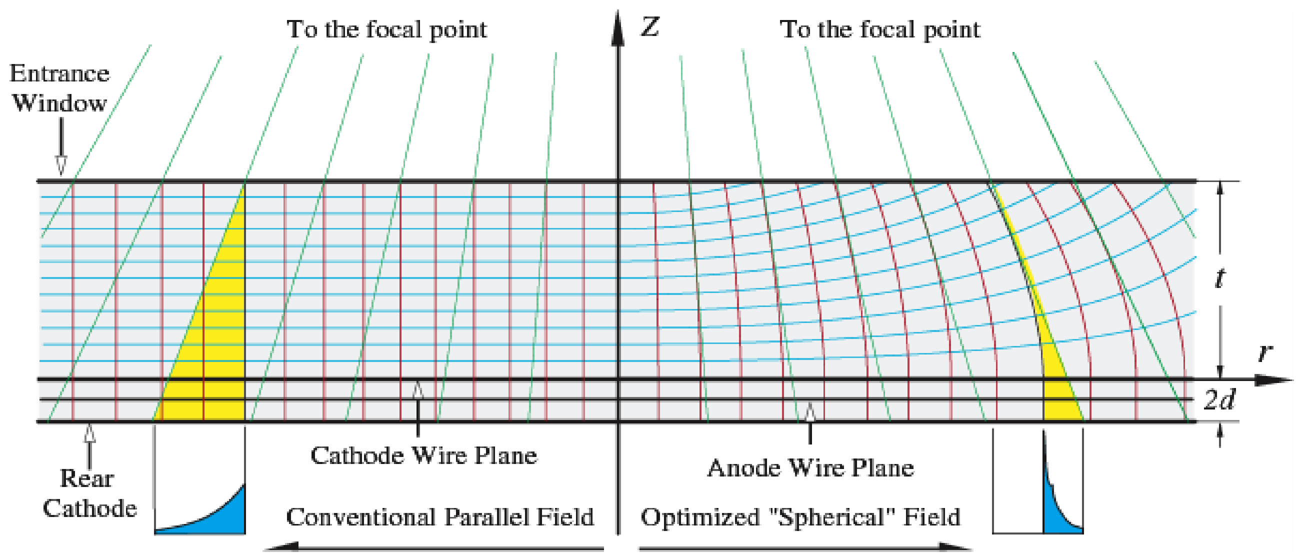
2. D >> L: (high ^{3}He pressure, slow neutrons, thick gas depth…) $\quad \sigma = L \cdot \sin\alpha$

Independent of gas depth

Parallax Reduction in a Gas Chamber

- Spherical Surface (tiled)
  - Ionization Chambers
  - Pin Arrays
- Conical Surface
  - GEMs
  - MWPCs
- Cylindrical Surface
  - PSD Tubes
  - MWPCs
  - GEMs
- Flat Surface
  - MWPCs
  - MSGCs
  - GEMs





Challenges to ^{3}He Based Detectors

- Large Area
  - Multiple detector system; PSD tubes.
- High Position Resolution
  - High stopping gas pressure
- High Detection Efficiency
  - High ^{3}He pressure
- High Counting Rate
  - Micro-pattern detectors
  - Low gas gain, unity gain operation
  - Parallel readout, local position encoding
- Close collaboration between detector physicists and electronics engineers

For a planar detector, the window minor dimension a, window thickness t and the total gas pressure P must follow:

$$P\, a^2 / t^{\,2} = \text{const.}$$